Practical Considerations for Selecting Operational Amplifiers

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Operational amplifiers are perhaps the most ubiquitous of analog building blocks, used in virtually every circuit to perform countless analog functions. Ironically, op amps are the rare analog component with near standard pin-configurations, yet there is no consistency of specifications from one manufacturer to the next (or even from one amplifier to the next). Moreover, the op amp is probably the most-specified and characterized analog building block, with data sheets providing pages and pages of tables and graphs.

Faced with literally hundreds of amplifiers offered by tens of manufacturers, even experienced engineers find the task of selecting the best op amp for a given application daunting. It need not be: with a basic understanding of the fundamental characteristics of op amps and the position the amplifier takes in the signal chain, a stepwise approach can quickly narrow the choice of amplifiers suited to a given application to manageable few:

- eliminate incompatible process technologies – consider signal source & load
- eliminate devices which don't meet power supply constraints
- ac or dc: choose speed or precision (sometimes both)
- make power consumption tradeoffs: speed, noise, drive
- eliminate special features not needed and/or identify characteristics required
- evaluate remaining amplifiers against application requirements

The author has used this technique to effectively assist hundreds of engineers choose amplifiers for a wide variety of applications. In the most basic of amplifier circuits – where "any op amp will do" – or in some more esoteric applications, it is sometimes more expedient to talk with an applications engineer who can pull from experience to identify the best op amp using more tailored criteria. This discussion is not intended to apply to the class of high-speed amplifiers commonly referred to as "wideband" or "video" amplifiers, and assumes packaging and thermal management are not at issue.

Basic "Ideal" Op Amp Characteristics

Before examining the advantages (and disadvantages) inherent to amplifiers manufactured in the various fabrication technologies commonly used today, it may be helpful first to review the basic characteristics of an "ideal" op amp. It is convenient to group them by input characteristics, output characteristics, power supply characteristics, and transfer characteristics, as this facilitates evaluation of the requirements of a real amplifier in a signal chain:

<u>Input characteristics</u>

- infinite input impedance, or zero input currents; no loading of signal source

$$Z_{IN} = \infty, \qquad I_{IN} = 0$$

- no constraints on differential or common-mode input signal

$$V_{ICR_{\pm}} \geq V_{CC_{\pm}}, \quad V_{ID_{\pm}} \geq \pm \left|V_{CC+} - V_{CC-}\right|$$

- perfectly matched, no dc (offset) voltage error
  $V_{IO} = 0$
- no noise sources
  $V_N = 0$, $I_N = 0$

Output characteristics

- infinite output current, sourcing or sinking
  $I_{OUT\pm} = \infty$
- "rail to rail" output swing
  $V_{OM\pm} = V_{CC\pm}$
- infinite step response (slew rate)
  $SR = \infty$
- no constraints on loads: resistive, capacitive, inductive

Power Supply characteristics

- no minimum supply voltage requirement; no maximum limit
  $V_{CC(MIN)} \geq 0$, $V_{CC(MAX)} \leq \infty$
- no power consumption (zero supply current); no power dissipation
  $I_{CC} = 0$, $P_D = 0$
- single- or split-supply

Transfer characteristics

- infinite open-loop gain
  $A_{VOL} = \infty$
- no frequency constraints
  $dc \leq f \leq \infty$
- no signal distortion introduced

…and of course it would be free.

Naturally no op amp exhibits any of these ideal characteristics. And there are many other op amp parameters which must ultimately be considered when selecting an op amp. However, understanding these few will enable the designer to quickly narrow his choices to a few amplifiers which can be more carefully evaluated.

Process Technologies vs. Op Amp Characteristics

Most op amps available today are manufactured in processes that can be generically categorized as bipolar, "biFET," or CMOS. Each of these accords certain relative "idealities" (and non-idealities) to an op amp. Some newer amplifiers are being manufactured in "biCMOS," which imparts the (usually) favorable characteristics of bipolar and CMOS technologies. Knowing these basic characteristics can allow the engineer choosing an op amp to eliminate broad classes immediately, significantly narrowing his choices.

Again considering the amplifier from the perspective of inputs, outputs, power supply, and transfer characteristics, these processes generally impart the following traits:

Table 1

These are not to be taken as absolutes. Many manufacturers exploit process limits and use clever design techniques to extend the capabilities of their processes to offer exceptional amplifiers targeted at more niche applications. New lower-voltage processes are improving the ac characteristics of CMOS amplifiers, and new topologies are addressing some of the shortcomings of earlier designs. New processes, like biCMOS, are further dimming the distinctions.

Still, in many cases, these basic characteristics do apply and can be used to effectively exclude many amplifiers from consideration. Power supply constraints, discussed in the next section, are especially limiting for some processes. Other considerations, like signal source and loads, can also steer one towards one technology versus another. More subtle characteristics of process technologies, outside the scope of this paper, can play a role in determining which is the best for a given application.

Power Supply Constraints

Armed with this basic understanding of process-related strengths and weaknesses, the easiest first cut against available amplifiers is made based on power supply voltage, minimum or maximum. Consider the supply voltage characteristics in the table above; some conclusions:

- CMOS amplifiers are not suited for higher-voltage systems, V_{CC} > ~18 V (and in many cases even lower)
- biFETs won't work in low-voltage systems, V_{CC} < ±3.5 V
- biFETs are not designed for single-supply operation; they can be used (any op amp can) – if the supply voltage is adequate – but careful (and inconvenient) attention must be paid to signal and load referencing
- some bipolar amplifiers are designed for single supply operation; still, CMOS would be the logical place to start looking unless other characteristics were more critical

By eliminating or focusing on one or more technologies, you not only remove hundreds of amplifiers from contention, but frequently also limit the number of manufacturers you must consider. Many manufacturers offer only bipolar amplifiers; a select few are prolific in CMOS; biFETs are similarly distributed. (It's worth noting that most manufacturers exploit their technology of choice to optimize those characteristics inherently better in that technology. This knowledge proves useful as you further narrow your selection based on performance criteria.)

Signal Characteristics: ac vs. dc

Recognizing a signal's ac and dc characteristics will also guide the choice of amplifier for a given sub-circuit:

- dc or slow-moving signals typically require little bandwidth; unless there is a step-function, slew rate and settling time are also of lesser importance
- ac signals place significant requirements on gain-bandwidth and slew rate; dc precision is frequently unimportant
- ac-coupled signals don't require precision-grade op amps; however, dc-coupled ac signals may
- small signals require higher-precision amplifiers
- precision and low noise become more critical in digital systems as the number of bits of resolution increases

Many applications can be characterized as essentially dc or ac, leading one to focus on a different set of amplifier characteristics. It's useful knowing which manufacturers concentrate on characteristics like higher precision, lower noise, or other performance indices when setting out to select an amplifier.

AC performance comes with other tradeoffs, not the least of which is power consumption. In fact, power consumption frequently becomes the pivotal parameter in finalizing op amp selection…

Power Consumption vs. Performance

In many systems, power consumption is a critical parameter driving the selection of an op amp. Engineers find themselves having to make difficult decisions trading power consumption for required performance. There are some first-order relationships that drive these decisions:

- ac performance – slew rate, bandwidth, settling time, … – come at the expense of power consumption (increased supply current)

  $SR \propto I_{CC}$, $BW \propto I_{CC}$, $t_s \propto I_{CC}$
- noise figure varies inversely to first-stage current; hence lower noise op amps require higher current

  $V_N \propto 1/I_{CC}$
- in many families of amplifiers, output drive is proportional to supply current

  $I_O \propto I_{CC}$

Frequently manufacturers offer two or more power options of the same operational amplifier. Making the judicious trade off between "lowest power" and required ac performance, noise, or output drive is often among the first decisions a designer must take.

The Final Cut

The final step in choosing an amplifier is usually a matter of a more thorough comparison of key specifications and performance graphs to determine the best fit. A few words of caution:

- While op amp pin configurations are largely standardized, parametric specifications are not. Test conditions vary, usually to showcase the amplifier at its best ("specsmanship"). Compounding this is the technology mix: selecting an amplifier strictly on a comparison of a few specifications fails to comprehend the sometimes subtle but critical characteristics of bipolar, CMOS, or biFET circuits. In this, especially, electronic selection guides can be misleading, yielding a mix of incompatible amplifiers as a consequence of searching a database of raw numbers. Paper selection guides are often a better place to start as factory "experts" typically group amplifiers so that an "apples to apples" comparison can be made.

- <u>Never</u> choose an op amp based solely on specifications! It is a rare circuit that operates with signals and loads connected in the configurations parameters are specified under. It's no coincidence op amp data sheets are heavy with graphs plotting performance against so many variables.. Unspecified – sometimes undesirable – characteristics typically turn up in these curves. Understanding how your op amp is configured and extrapolating from the curves back to the specifications is critical in ensuring your selection will perform as expected.

- Be aware – but beware – of special features or added performance: they come with a price and, almost always, some tradeoff in performance. Some applications require rail-to-rail inputs or outputs, temperature compensation, input clamping, etc. Many do not. Don't be hasty to pay for "features" you don't really need. An applications engineer can be your best resource for identifying an amplifier which meets special requirements, and for making sure you know the hidden tradeoffs in performance you may need to compensate for.

- Finally, a note about models: amplifier models are a poor tool for simulating performance of a real circuit. They are, at best, useful for making sure nothing has been left disconnected. Models available today are typically derived from the data sheet specifications such that if the test circuit were modeled, the simulator would output the specification. They fail completely to comprehend boundary conditions or second-order effects, and are of little use predicting behavior of anything but the most basic textbook configurations. With op amps, there is no substitute for evaluating the real circuit in the lab.

In summary, choosing an op amp doesn't need to be the intimidating task it can seem to be. Making some common sense decisions can lead the design engineer to a few devices from which a more studied selection can be made.