Test circuits – Measuring component specifications

General

Any electronic component is characterized by a set of specifications that allow designers to assess performance, power consumption, operating limits, etc. Essential aspects reflected in performance data are often summarized in a *behavioural* description of the component.

Whereas integrated circuit (IC) design relies on circuit-level descriptions based on elementary devices such as transistors, diodes, capacitances, that can be readily associated to different aspects of the IC manufaturing process, a behavioral model is aimed at supporting functional, system-level design.

Binary variables and the rules of Boolean algebra are used in the functional description of digital circuits, which means a complete change in the analytical approach. The behavioral model of an analogue circuit, on the other hand, is still provided in circuit form but basic blocks correspond to a higher-level abstraction. In the simplest case a signal amplifier might be represented, for instance, by a voltage-controlled voltage source, an elementary description that misses any internal detail and focusses on the primary function of the device.

Behavioral models are particularly useful in computer-assisted simulation analysis, since they greatly simplify system level modeling and allow faster simulation runs. Besides computational efficiency, simulation results should be accurate enough for reliable prediction of real system performance. This is essential to enable designers to minimize expensive prototyping and go through revisions and design iterations mostly by simulation. This emphasizes the importance of measurements to extract relevant component data.

Electronic components are usually specified by providing *typical*, *minimum* and *maximum* values, as suitable, for a number of quantities. Such values are the result of manufacturers taking measurements on sample production components, thus accounting also for parametric variability related to manufacturing processes. The same kind of measurements may be carried out by users on selected devices, to obtain values specific to individual components or the evidence needed to test conformance to specifications.

Of course, each particular component type may require different, dedicated test circuits. Consequently it is hard to generalize, but it must be remembered that the purpose of test circuits is twofold:

- create suitable operating conditions for the device under test (DUT);

- enable test signals to be accurately measured.

Test engineers are usually expected to be able to develop their own test fixtures. Instrumentation manufacturers may develop specific measurement systems in cases where the effort can be justified by a corresponding return.

An example: the operational amplifier

Operational amplifiers (*OpAmps*) are among the most widely employed analogue electronic components. This explains their choice to illustrate some test circuit examples in this chapter. As already noted, measurement circuits are component-specific, however they will be discussed with the aim of evidencing general criteria and rules-of-thumb that may be reasonable to follow in general.

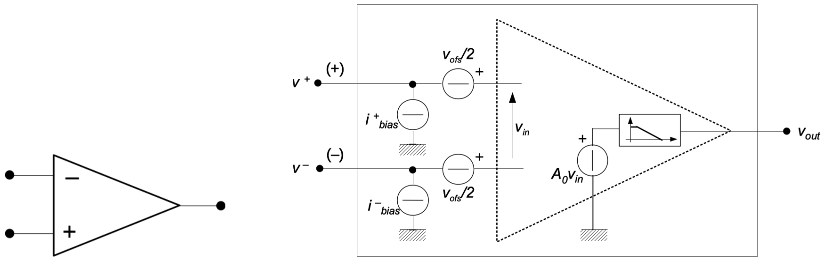
In circuit schematics, an *OpAmp* is usually represented by the symbol shown in Fig. 1. This reminds that the device has a single, ground-referenced output and two differential inputs called, respectively, *inverting* ($-$) and *non-inverting* ($+$) inputs.

Preliminary analysis of any *OpAmp*-based circuit is based on some well-known "idealized" assumptions, namely:

- voltage gain is *infinite* (very large in practice, order of 10^5 or more);
- input impedance is *infinite* (order of di 10^8 Ω);
- output impedance is null (a few Ω in practice).

Consequences, again in idealized form, are summarized here for convenience:

- current drawn by the inputs is zero, since input impedance is infinite;
- since output voltage must be finite and voltage gain is close to infinite, the voltage difference between the inverting and non-inverting inputs is quite small. The two inputs may be assumed to be *equipotential* for most practical purposes;
- any intensity of output current can be obtained, since output impedance is negligible.



(a) Graphic symbol.

(b) A reduced behavioural model – only input currents, voltage bias and frequency-dependent gain are evidenced.

Figure 1: Operational amplifier.

Of course, real components may only get close to these assumptions, to varying degrees of approximation and under suitable conditions. At least some of them would be challenged by a more detailed analysis in any *OpAmp*-based circuit, more complex models being usually needed. An example is provided in Fig. 1b, where:

- voltage sources at the input represent the *OpAmp* offset voltage;
- current sources at the input account for bias currents through the input terminals;
- a voltage-controlled voltage source represents finite gain;
- a frequency-dependent block introduces a low-frequency pole that shapes the frequency response in most *OpAmps*.

It can be noted that there is no correspondence between the actual *OpAmp* circuitry and the schematic in Fig. 1b, yet this can be translated into a netlist providing accurate circuit simulation results, at least for some aspects of circuit operation.

The circuit model of Fig. 1b reproduces only a few of the characteristics reported in a component specifications (for example, input impedance to ground and common-mode rejection ratio are not accounted for). A manufacturer would typically provide a complete *macromodel* for SPICE simulation whose parameters, taken from specifications, allow a faithful reproduction of actual device behaviours.

Any form of analysis can only be as good as the circuit models it employs. It is important, then, to be able to accurately measure device parameters the are to be fed into those models, be they equations or simplified equivalent circuits.

Operational amplifier measurements

Operational amplifiers are meant to be employed in feedback configuration. Some features, in particular their extremely high gain, make measurements on the component alone rather difficult because of the very large difference between input and output voltage levels. Therefore, test circuits for measuring *OpAmp* parameters, including open-loop gain, often employ suitable feedback configurations with additional components. Of course, the effect of the test circuit on the measured device has to be determined and, if necessary, compensated for. In the following, a few test circuit configurations will be presented.

Unit-gain bandwidth

The open-loop gain of an operational amplifier can be expressed in most cases by the following frequency response:

$$G_{ol}(f) = \frac{A_0}{1 + j2\pi f T_1} \tag{1}$$

where A_0 is the zero-frequency, or direct-current (DC) gain and T_1 is the time constant associated to the low-frequency pole that is designed into the amplifier circuit. Consequently, the open-loop 3-dB bandwidth is $f_{ol} = \frac{1}{2\pi T_1}$. Its order of

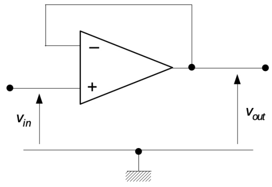


Figure 2: Operational amplifier in unit-gain voltage follower configuration.

magnitude is in general between some Hz and a few tens of Hz, typical values changing with different component types.

The gain of the voltage-follower configuration shown in Fig. 2, also called a *unit-gain* amplifier, is:

$$G_{vf}(f) = \frac{G_{ol}(f)}{1 + G_{ol}(f)} \cong \frac{1}{1 + j2\pi f \frac{T_1}{A_0}} = \frac{1}{1 + j\frac{f}{f_T}} \tag{2}$$

where parameter $f_T = \frac{A_0}{2\pi T_1} = A_0 f_{ol}$ is called ***unit-gain bandwidth***.

Its value, typically in the MHz range, can be measured simply by determining the frequency response of a unit-gain circuit employing the DUT. The test circuit for measuring f_T employs only the DUT in suitable voltage follower configuration and a power supply. Unit-gain bandwidth is simply the frequency at which measured gain is 3 dB less than the DC (zero-frequency) or low-frequency gain. Since in the test configuration DC gain is 1, it suffices to look for the frequency where the ratio of output to input voltage drops to $1/\sqrt{2} \cong 0.707$.

Instruments needed for this purpose are a ***sinewave generator*** with variable output frequency and amplitude; a ***two-channel oscilloscope*** to measure the voltage follower input and output. Other measuring instruments may be employed alternatively, however the oscilloscope provides better flexibility by allowing simultaneous visualization of the circuit input and output.

It should be reminded from Fig. 1b that bias currents and input voltage offsets can produce a significant voltage offset at the output. In other words, the output sinewave may have a non-zero mean value, therefore care should be taken to measure only its AC component. This can be achieved by choosing a suitable measurement function from the oscilloscope menu, either peak-to-peak or RMS(AC) voltage. Since the low-frequency attenuation associated with AC coupling does not affect the determination of unit-gain bandwidth, AC coupling could be selected for the oscilloscope channels as an alternative. It is advisable in this case to use the same coupling for *both* channels to avoid channel mismatch errors when measuring gain.

Open-loop gain

The simple circuit configuration of Fig. 2 does not allow to characterize an operational amplifier entire open-loop response. In principle, a simple input-output measurement using sinewaves at different frequencies would suffice. However, the high gain of the open-loop DUT makes measurement harder. To prevent the output from going into voltage saturation, the input sinewave ought to be in the

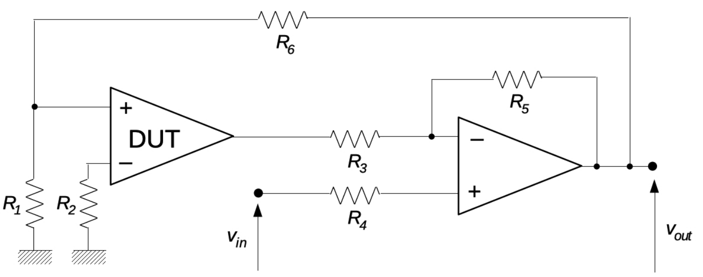


Figure 3: Test circuit for operational amplifier open loop gain measurement.

μV range, which is often impractical. For this reason, in the circuit schematic of Fig.3 the DUT is inserted into a feedback loop that includes an auxiliary operational amplifier.

With this circuit, test voltage v_{in} provided by an external waveform generator is sent to the non-inverting input of the auxiliary operational amplifier through resistance R_4. The DUT output is sent to the inverting input of the same amplifier through resistance R_3 and it is assumed that $R_3 = R_4$, so that the auxiliary amplifier is presented with an approximately balanced differential input. The condition $R_2 = R_1$ is required to balance the effect of DUT input bias currents.

The inner feedback loop provides gain, that is determined by resistance R_5 whose value should be high enough (for instance, $R_5 > 400 \cdot R_3$ to also minimize the difference between current through R_3 and R_4, the latter being virtually nil, except for bias current.

The outer feedback loop in the circuit of Fig. 3 acts as a voltage divider to bring a fraction of the auxiliary amplifier output voltage v_{out} back into the inverting input of the DUT. For the operational amplifier under test, the input voltage value is:

$$v_{DUT_{in}} = v_{out} \frac{R_1}{R_1 + R_6}$$

Ideally, the non-inverting and the inverting inputs of the auxiliary operational amplifier are at the same potential, therefore the test circuit actually forces the DUT output to take on the same value as the waveform generator input: $v_{DUT_{out}} = v_{in}$. Both the auxiliary amplifier and the signal generator output voltage can be measured and from these the DUT gain can be computed as:

$$\text{DUT gain} = \frac{v_{DUT_{out}}}{v_{DUT_{in}}} = \frac{v_{in}}{v_{out} \frac{R_1}{R_6 + R_1}} \tag{3}$$

This equation shows how open-loop gain can be determined by measuring the test circuit input and output voltages *and* the values of resistances R_1, R_6. Actual resistor values should be *measured* to ensure the value gain is correctly determined.

The open-loop gain characteristic can thus be determined by simple frequency response measurements. As long as the auxiliary amplifier behaves correctly as a linear device, its behavior is irrelevant to measurement accuracy, at least to a first approximation.

An indicative list of resistor nominal values for the circuit of Fig. 3 is reported below as an example. Different values can be chosen, as long as indications reported in the text above are kept into account.

R_1	R_2	R_3	R_4	R_5	R_6
47 Ω	47 Ω	100 Ω	100 Ω	47 kΩ	47 kΩ

Table 1: Example of component values for the test circuit of Fig. 3.

Frequency response

The measurement procedure is briefly summarized as follows:

1. connect a power supply to the test circuit and power it up;
2. connect the waveform generator to the test circuit and to an oscilloscope input channel, so that the test sinewave can be measured (using a ‘T’ coaxial connector). Set an appropriate waveform amplitude;
3. using a coaxial cable with suitable wire clips (or “banana” plugs), acquire the test circuit output and send it to an oscilloscope input channel;
4. determine a set of frequencies where the DUT gain is to be determined and repeat the measurement at each frequency.

Note: this is a low-frequency measurement and signal amplitude is expected to be rather small. In this case it is not advisable to use a compensated passive probe: the effect of cable capacitance is negligible at these frequencies, whereas probe attenuation may reduce signal amplitude exceedingly.

IMPORTANT
The open-loop gain characteristic of an operational amplifier is characterized by a **low-frequency** pole, therefore the frequency response measurement range should be chosen accordingly. A lower frequency limit around 1-2 Hz is suggested.

AC coupling of the oscilloscope input channels is to be avoided in this case, since the frequencies of interest would be unacceptably attenuated. Since signal v_{out} can be rather noisy at the lowest frequencies, peak-to-peak voltage measurement is best avoided as well, leaving RMS(AC) as the preferred measurement function. Furthermore, with noisy measured signals it may be advisable to employ the ***averaging*** acquisition mode for the oscilloscope, remembering that a **stable** trigger is essential to the averaging acquisition mode.

Gain and phase shift

At each frequency, measurements should provide the following quantities:

- amplitude of the test circuit input sinewave v_{in};
- amplitude of the test circuit output sinewave v_{out};

- delay τ of the output sinewave from the input sinewave.

The frequency indication provided by the waveform generator can be considered accurate enough for the purposes of this exercise.

Determining DUT gain

It is important to remember that the expression for DUT open-loop gain is given by (3). Take care to consider the correct ratio of quantities.

Gain values are often expressed in dB, in which case gain should be calculated as:

$$G[\mathrm{dB}] = 20\log_{10}\frac{v_{in}}{v_{out}\frac{R_1}{R_1+R_6}} \tag{4}$$

Determining DUT phase

It is important to remember that phase is determined from the DUT input-output delay. The test circuit *input* signal corresponds to the *output* of the operational amplifier under test, whereas the test circuit *output* signal, suitably scaled, provides the *input* to the operational amplifier. **Care is needed** to determine the correct reference for this measurement.

After the delay τ has been measured, phase shift is directly determined as:

$$\Delta\phi = -\tau\cdot f_0\cdot 2\pi[\mathrm{rad}] \qquad \text{or:} \qquad \Delta\phi = -\tau\cdot f_0\cdot 360[\mathrm{degrees}]$$

where f_0 is the test sinewave frequency.

Test circuit analysis

So far, only the basic principle of operation has been discussed for the test circuit. Consideration will now be given to possible limitations that need to be taken into account.

Of course, deviations from nominal resistance values can be expected for all resistors in the circuit. However, relative variations within tolerance limits are not critical, since the measured operational amplifier gain is quite large. For a common value of resistor tolerance such as ±5% resistance ratio uncertainty in (3) could be in the order of 10%. When the dB expression (4) is considered, this translates into a ±0.1 dB uncertainty.

Of greater relevance to the understanding of test circuit operation is the behavior of the auxiliary amplifier. In particular, the effect of its frequency-dependent open-loop gain characteristic needs to be investigated. The relevant circuit is shown in Fig. 4. Assuming an ideal behavior for the operational amplifier and applying superposition, its input-output relationship would be expressed by:

$$v_{out} = \frac{R_5+R_3}{R_3}\cdot\left(v_{in} - \frac{R_5}{R_5+R_3}v_{DUT_{out}}\right) \tag{5}$$

that, assuming $\frac{R_5}{R_5+R_3}\cong 1$, yields (3). However, it must be remembered that the open-loop gain characteristic of the operational amplifier in Fig. 4 has the same form given in (1). For a measurement of this kind, its influence cannot be neglected in a more detailed analysis.

Using symbols $A_{0,2}$ and T_2 to differentiate the parameters from those of the DUT, the unit-gain bandwidth of the device is: $f_{T_2} = A_{0,2}/(2\pi T_2)$. To account for its effect (5) needs to be replaced by the equation:

$$v_{out} = \frac{1}{1 + j\frac{f}{f_T} \cdot \frac{R_5+R_3}{R_3}} \cdot \left[\frac{R_5 + R_3}{R_3} \cdot \left(v_{in} - \frac{R_5}{R_5 + R_3} v_{DUT_{out}} \right) \right] \qquad (6)$$

The first term in the expression shows that the test circuit amplifier is band-limited. Its upper cut-off frequency is:

$$f_{Aux} = \frac{f_{T_2}}{\frac{R_5+R_3}{R_3}} \qquad \text{with:} \qquad \frac{f_{T_2}}{A_{0,2}} < f_{Aux} < f_{T_2}. \qquad (7)$$

To understand the consequences of (6) it is interesting to consider a numerical example. Let the two operational amplifiers in the test circuit of Fig. 3 have the same unit-gain bandwidth, $f_{T_1} = f_{T_2} = 1$ MHz. Assuming $A_0 = 10^5$ and resistance values R_3 and R_5 such that $\frac{R_5+R_3}{R_3} \cong 5 \times 10^3$, the DUT low-frequency pole would be located at 10 Hz, while the auxiliary amplifier cut-off frequency would be approximately 2 kHz. Thus, as test frequency increases the circuit output voltage v_{out} is progressively attenuated so that, according to (3), DUT gain would appear to increase. This seemingly inexplicable behavior is actually caused by the bandwidth limitation of the test circuit.

For a more rigorous treatment, it can be considered that the DUT input-output equation is:

$$v_{DUT_{out}} = \frac{A_0}{1 + j2\pi f T_1} \cdot v_{DUT_{in}} = \frac{A_0}{1 + j2\pi f T_1} \cdot v_{out} \frac{R_1}{R_1 + R_6} \qquad (8)$$

and combining equations (6) and (8) one has:

$$\frac{v_{in}}{v_{out} \frac{R_1}{R_6+R_1}} = \frac{A_{0,1}}{1 + j2\pi f T_1} + \frac{R_6 + R_1}{R_1} \cdot \frac{R_3}{R_5 + R_3} \left(1 + j\frac{f}{f_{Aux}} \right) \qquad (9)$$

where it is again assumed $\frac{R_5}{R_5+R_3} \cong 1$. The second term in this measurement equation accounts for the bandwidth limitation in the test circuit. Its contribution becomes progressively more significant at higher test frequencies and it can

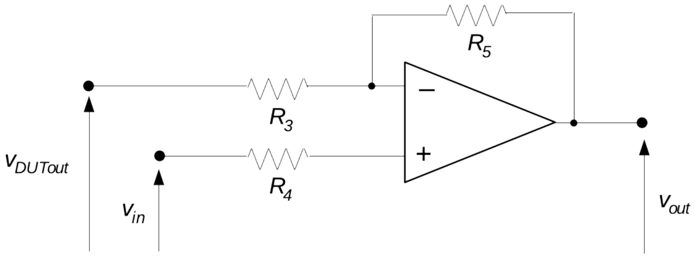


Figure 4: Auxiliary amplifier in the open loop gain test circuit.

be verified that, with the values assumed above, it would exceed 10% at about 10 kHz.

This analysis shows that the frequency range might be extended if the auxiliary operational amplifier had a wider unit-gain bandwidth. For instance, with $f_{T_2} = 25$ MHz measurement could be accurate up to about 50 kHz.