# Op-amps

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## Op-amp Information

- https://mysite.du.edu/~etuttle/electron/elect3.htm
- https://bjpcjp.github.io/pdfs/cmos_layout_sim/ch24-op-amps.pdf
- https://www.allaboutcircuits.com/technical-articles/negative-feedback-part-1-general-structure-and-essential-concepts/

## Bandwidth Measurement

Measuring the bandwidth of an operational amplifier (op-amp) means determining the frequency range over which it can amplify signals accurately. Bandwidth is typically defined as the frequency at which the gain drops by 3 dB compared to its low-frequency value. There are two closely related bandwidth concepts:

- **Small-signal (linear) bandwidth**: The frequency at which the gain drops by 3 dB (to 0.707 of its mid-band value).
- **Gain-Bandwidth Product (GBW)**: For most voltage-feedback op-amps, the product of closed-loop gain and bandwidth is approximately constant.

```
Bandwidth = GBW / Closed-loop gain
```

#### Step-by-step Procedure:

1. Configure the op-amp in a non-inverting amplifier configuration with a moderate gain (e.g., 5 or 10).
2. Apply a small-amplitude sine wave (typically 50–100 mVpp) at a low starting frequency, such as 1 kHz.
3. Measure the mid-band gain (Vout/Vin) and use this as the reference gain.
4. Sweep the input frequency upward while monitoring the output amplitude.
5. Identify the frequency at which the output amplitude falls to 0.707 of the mid-band value. This frequency is the closed-loop bandwidth.

#### Measuring Unity-Gain Bandwidth (GBW)

To measure the GBW directly, configure the op-amp as a voltage follower (gain = 1). Sweep the frequency and find the −3 dB point. This frequency approximates the unity-gain bandwidth. Note: Always verify that the op-amp is unity-gain stable before using this method.

#### Common Measurement Pitfalls

- Slew-rate limitation is a frequent error. If the output waveform becomes triangular at high frequency, the op-amp is slew-rate limited and the measurement is invalid. Reduce the input amplitude to correct this.
- Additionally, avoid excessive output loading and use a high-impedance oscilloscope probe (10×) to reduce measurement errors.
- Ensure proper power-supply decoupling and watch for instability or oscillations caused by capacitive loads.

# Input Offset Voltage (Vos) Measurement

The input offset voltage (Vos) of an operational amplifier is the small differential DC voltage that must be applied between the inputs to force the output to exactly zero. Measuring Vos is an important step when evaluating DC accuracy, especially for precision, instrumentation, or low-level signal applications. Typical input offset voltage ranges:

- General-purpose op-amps: 0.5 mV to 5 mV
- Precision op-amps: 1 µV to 100 µV
- Chopper / auto-zero op-amps: < 1 µV

### Measurement Method (Non-Inverting Amplifier)

The most reliable way to measure Vos is to amplify it using a high closed-loop gain and then calculate it back from the measured output voltage.  Test Configuration:

- Configure the op-amp as a non-inverting amplifier
- Connect the non-inverting (+) input to ground
- Use a resistive feedback network to set a high gain (e.g. 100–1000)
- Power the op-amp with normal operating supply voltages.
- Allow the circuit to thermally stabilize (5–15 minutes recommended).
- Ensure no signal is applied to the input.
- Measure the DC output voltage using a high-resolution DMM.
- Calculate Vos using the formula below.

```
Vos = Vout / Gain
```

### Compensation for Input Bias Current

Input bias currents flowing through source resistances introduce additional offset voltage. To cancel this effect, add a bias compensation resistor.  Bias compensation resistor:

```
Rcomp = Rf || Rg
```

Place Rcomp between the non-inverting input and ground.

### Special Considerations for Chopper and Auto-Zero Op-Amps

Chopper and auto-zero op-amps have extremely low Vos but may exhibit output ripple due to internal switching. Use output filtering or averaging measurements to obtain a stable DC reading.

### Temperature Effects

Input offset voltage drifts with temperature, typically specified in µV/°C.
For accurate results, maintain a stable ambient temperature and avoid airflow or direct heat sources.

### Measurement Best Practices

- Use short, symmetric input wiring
- Avoid thermoelectric junctions and touching nodes during measurement
- Use proper supply decoupling capacitors

## Slew Rate Measurement

This describes a practical laboratory setup and step-by-step procedure to measure the slew rate of an operational amplifier. Slew rate is defined as the maximum rate of change of the output voltage and is usually expressed in volts per microsecond (V/µs). The slew rate is measured by applying a fast, large-signal step input to the op-amp and observing the output voltage transition. When slew-rate limited, the output waveform exhibits a linear rising or falling edge. The slope of this edge represents the slew rate.

### Test Configuration

Configure the op-amp as a voltage follower (unity-gain buffer). This ensures the measured slew rate is limited by the internal op-amp performance rather than external gain components.

- Decoupling capacitors (e.g. 100 nF close to supply pins)
- Waveform: Square wave
- Amplitude: Large enough to force slew-rate limiting (e.g. ±2 to ±5 V)
- Frequency: Low enough that the output fully settles (e.g. 1–10 kHz)
- Rise/fall time of generator: At least 5× faster than op-amp slew capability
- Power the op-amp and allow a few minutes for thermal stabilization.
- Apply the square-wave signal to the non-inverting input.
- Observe input (CH1) and output (CH2) simultaneously on the oscilloscope.
- Adjust timebase to clearly display the output rising and falling edges.
- Identify the linear portion of the output transition (slew-limited region).
- Measure ΔV and Δt using oscilloscope cursors.
- Calculate slew rate using the formula below.

```
Slew Rate (SR) = ΔV / Δt
```

### Important Notes and Common Errors

- Ensure the op-amp is not bandwidth-limited instead of slew-limited. A rounded exponential edge indicates bandwidth limitation.
- Avoid output saturation; keep transitions within the linear output swing region.
- Use short probe ground leads to avoid ringing and measurement artifacts.

# CMRR Measurement

This describes the procedure to measure the Common-Mode Rejection Ratio (CMRR) of an operational amplifier. CMRR is a key parameter that indicates how well the op-amp rejects signals that are common to both inputs. The Common-Mode Rejection Ratio (CMRR) is defined as the ratio of differential gain (Adiff) to common-mode gain (Acm):

```
CMRR = Adiff / Acm
CMRR (dB) = 20 · log10(Adiff / Acm)
```

### Principle of Measurement

In this test, the same AC signal is applied simultaneously to both op-amp inputs (common-mode signal). Ideally, the output should not change. Any observed output variation is due to finite common-mode gain. By measuring this output and comparing it to the applied input, the common-mode gain and CMRR can be calculated.

### Test Procedure

Configure the op-amp in a differential amplifier configuration with known differential gain. Apply the same AC voltage to both the non-inverting and inverting inputs through matched resistors, ensuring a purely common-mode excitation. To minimize resistor-induced errors, all resistors in the input network should be closely matched. Steps:

- Signal type: Sine wave
- Amplitude: 0.5–2 V RMS (small enough to avoid output saturation)
- Frequency: Typically 100 Hz to 1 kHz (unless frequency-dependent CMRR is required)
- Measurement Procedure
- Power the op-amp and allow it to thermally stabilize.
- Apply the same AC voltage to both inputs using matched resistors.
- Verify that the applied signal is equal in amplitude and phase on both inputs.
- Measure the output AC voltage caused by the common-mode input.
- Calculate the common-mode gain (Acm).
- Obtain or measure the differential gain (Ad).
- Calculate CMRR using the formulas below.

```
Common-mode gain:  Acm = Vout / Vcm
CMRR (dB) = 20 · log10(Ad / Acm)
```

## Op-amp Stability

- https://www.ti.com/lit/an/slyt087/slyt087.pdf?ts=1687347593525&ref_url=https%253A%252F%252Fwww.google.com%252F
- https://www.k-state.edu/edl/docs/pubs/technical-resources/Technote9.pdf
- https://electronics.stackexchange.com/questions/530698/whats-the-need-for-a-small-capacitor-in-the-negative-feedback-parallel-to-a-fee
- https://electronics.stackexchange.com/questions/390986/non-inverting-op-amp-configuration-with-capacitor
- https://www.edn.com/the-impact-of-input-capacitance-on-op-amp-stability/
- https://www.analog.com/en/analog-dialogue/articles/techniques-to-avoid-instability-capacitive-loading.html
- https://www.eevblog.com/forum/projects/compensation-methods-in-current-sink-circuits/
- https://www.eevblog.com/forum/projects/dynamic-electronic-load-project/msg462562/#msg462562