APPENDIX B

Understanding Op Amp Parameters

B.1 Introduction

This appendix explains op amp data sheet parameters. There are usually three main sections of electrical tables in op amp data sheets.

B.1.1 Absolute Maximum Ratings

Absolute maximum ratings are those limits beyond which the life of individual devices may be impaired and are never to be exceeded in service or testing. Limits, by definition, are maximum ratings, so if double-ended limits are specified, the term will be defined as a range (e.g., operating temperature range).

B.1.2 Recommended Operating Conditions

Recommended operating conditions have a similarity to maximum ratings in that operation outside the stated limits could cause unsatisfactory performance. Recommended operating conditions, however, do not carry the implication of device damage if they are exceeded.

B.1.3 Electrical Characteristics

Electrical characteristics are measurable electrical properties of a device inherent in its design. They are used to predict the performance of the device as an element of an electrical circuit. The measurements that appear in the electrical characteristics tables are based on the device being operated within the recommended operating conditions.

Table B.1 lists op amp condition and parameter abbreviations in alphabetical order plus their corresponding description and units.

As the name of this page implies, some of Table B.1 is composed of parameters and some test conditions. Test conditions are conditions placed on the op amp when the parameters are measured. Some abbreviations are used for both a condition and a parameter.

Units listed in the units column of Table B.1 are part of the standard SI units of measure. Multiplier prefixes such as p (pico), M (mega), etc. are often used in data sheets.

Table B.1: Op Amp Condition and Parameter Table.

Abbreviations	Parameter	Units
αI_{IO}	Temperature coefficient of input offset current	A/°C
αV_{IO} or α_{VIO}	Temperature coefficient of input offset voltage	V/°C
A_D	Differential gain error	%
A_m	Gain margin	dB
A_{OL}	Open-loop voltage gain	dB
A_V	Large-signal voltage amplification (gain)	dB
A_{VD}	Differential large-signal voltage amplification	dB
B_1	Unity gain bandwidth	Hz
B_{OM}	Maximum-output-swing bandwidth	Hz
BW	Bandwidth	Hz
c_i	Input capacitance	F
C_{ic} or $C_{i(c)}$	Common-mode input capacitance	F
C_{id}	Differential input capacitance	F
C_L	Load capacitance	F
$\Delta V_{DD\pm(or\ CC\pm)}/\Delta V_{IO}$, or k_{SVS}	Supply voltage sensitivity	dB
CMRR or k_{CMR}	Common-mode rejection ratio	dB
f	Frequency	Hz
GBW	Gain bandwidth product	Hz
$I_{CC\text{-}(SHDN)}$, $I_{DD\text{-}(SHDN)}$	Supply current (shutdown)	A
I_{CC}, I_{DD}	Supply current	A
I_I	Input current range	A
I_{IB}	Input bias current	A
I_{IO}	Input offset current	A
I_n	Input noise current	$A/\sqrt{Hz}$
I_O	Output current	A
I_{OL}	Low-level output current	A
I_{OS}, or I_{SC}	Short-circuit output current	A
CMRR or k_{CMR}	Common-mode rejection ratio	dB
k_{SVR}	Supply rejection ratio	dB
k_{SVS}	Supply voltage sensitivity	dB
P_D	Power dissipation	W
PSRR	Power supply rejection ratio	dB
θ_{JA}	Junction to ambient thermal resistance	°C/W
θ_{JC}	Junction to case thermal resistance	°C/W
r_i	Input resistance	Ω
r_{id}, $r_{i(d)}$	Differential input resistance	Ω
R_L	Load resistance	Ω
R_{null}	Null resistance	Ω
r_o	Output resistance	Ω
R_S	Signal source resistance	Ω
R_t	Open-loop transresistance	Ω
SR	Slew rate	V/S
T_A	Operating temperature	°C
t_{DIS} or $t_{(off)}$	Turn-off time (shutdown)	s
t_{EN} or $t_{(on)}$	Turn-on time (shutdown)	s
t_f	Fall time	s

Table B.1: Op Amp Condition and Parameter Table.—cont'd

Abbreviations	Parameter	Units
THD	Total harmonic distortion	%
THD + N	Total harmonic distortion plus noise	%
T_J	Maximum junction temperature	°C
t_r	Rise time	s
t_s	Settling time	s
T_S or T_{stg}	Storage temperature	°C
V_{CC}, V_{DD}	Supply voltage	V
V_I	Input voltage range	V
V_{ic}	Common-mode input voltage	V
V_{ICR}	Input common-mode voltage range	V
V_{ID}	Differential input voltage	V
V_{DIR}	Differential Input voltage range	V
$V_{IH\text{-}SHDN}$ or $V_{(ON)}$	Turn-on voltage (shutdown)	V
$V_{IL\text{-}SHDN}$ or $V_{(OFF)}$	Turn-off voltage (shutdown)	V
V_{IN}	Input voltage (DC)	V
V_{IO}, V_{OS}	Input offset voltage	V
V_n	Equivalent input noise voltage	$V/\sqrt{Hz}$
$V_{N(PP)}$	Broad band noise	V P—P
V_{OH}	High-level output voltage	V
V_{OL}	Low-level output voltage	V
$V_{OM\pm}$	Maximum peak-to-peak output voltage swing	V
$V_{O(PP)}$	Peak-to-peak output voltage swing	V
$V_{(STEP)PP}$	Step voltage peak-to-peak	V
X_T	Crosstalk	dB
Z_O	Output impedance	Ω
Z_t	Open-loop transimpedance	Ω
Φ_D	Differential phase error	Degree
Φ_m	Phase margin	Degree
	Bandwidth for 0.1 dB flatness	Hz
	Case temperature for 60 s	°C
	Continuous total dissipation	W
	Differential gain error	%
	Differential phase error	Degree
	Duration of short-circuit current	s
	Input offset voltage long-term drift	V/month
	Lead temperature for 10 or 60 s	°C

B.2 Temperature Coefficient of the Input Offset Current (αI_{IO})

The temperature coefficient of the input offset current, αI_{IO}, is defined as the ratio of the change in input offset current to the change in the die temperature. This is an average value for the specified temperature range.

αI_{IO} specifies the expected input offset current drift over temperature. Its units are μA/°C. I_{IO} is measured at the temperature extremes of the part, and αI_{IO} is computed as $\Delta I_{IO}/\Delta°C$.

Normal aging in semiconductors causes changes in the characteristics of devices. The input offset voltage long-term drift specifies how I_{IO} is expected to change with time. Its units are amperes/month.

B.3 Temperature Coefficient of Input Offset Voltage (αV_{IO} or α_{VIO})

The temperature coefficient of input offset voltage, αV_{IO} or α_{VIO}, is defined as the ratio of the change in input offset voltage to the change in the die temperature. This is an average value for the specified temperature range.

αV_{IO} specifies the expected input offset drift over temperature. Its units are V/°C. V_{IO} is measured at the temperature extremes of the part, and αV_{IO} is computed as $\Delta V_{IO}/\Delta°C$.

Normal aging in semiconductors causes changes in the characteristics of devices. The input offset voltage long-term drift specifies how V_{IO} is expected to change with time. Its units are μV/month.

B.4 Differential Gain Error (A_D)

The differential gain error parameter, A_D, is defined as the change in AC gain with change in DC level. The AC signal is 40 IRE (0.28 VPK) and the DC level change is ±100 IRE (±0.7 V). Typically tested at 3.58 MHz (NTSC) or 4.43 MHz (PAL) carrier frequencies. It is represented in units of percent. With the conversion to digital broadcast video, this parameter is quickly becoming irrelevant.

B.5 Gain Margin Parameter (A_m)

Gain margin, A_m, is defined as the absolute value of the difference in gain between the unity gain point and the gain at the −180 degrees phase shift point. It is measured open loop and expressed in units of decibels, dB.

Gain margin (A_m) and phase margin (Φ_m) are different ways of specifying the stability of the circuit. Since rail-to-rail output op amps have higher output impedance, a significant phase shift is seen when driving capacitive loads. This extra phase shift erodes the phase margin, and for this reason most CMOS op amps with rail-to-rail outputs have limited ability to drive capacitive loads. Fig. B.1 shows the gain margin graphically.

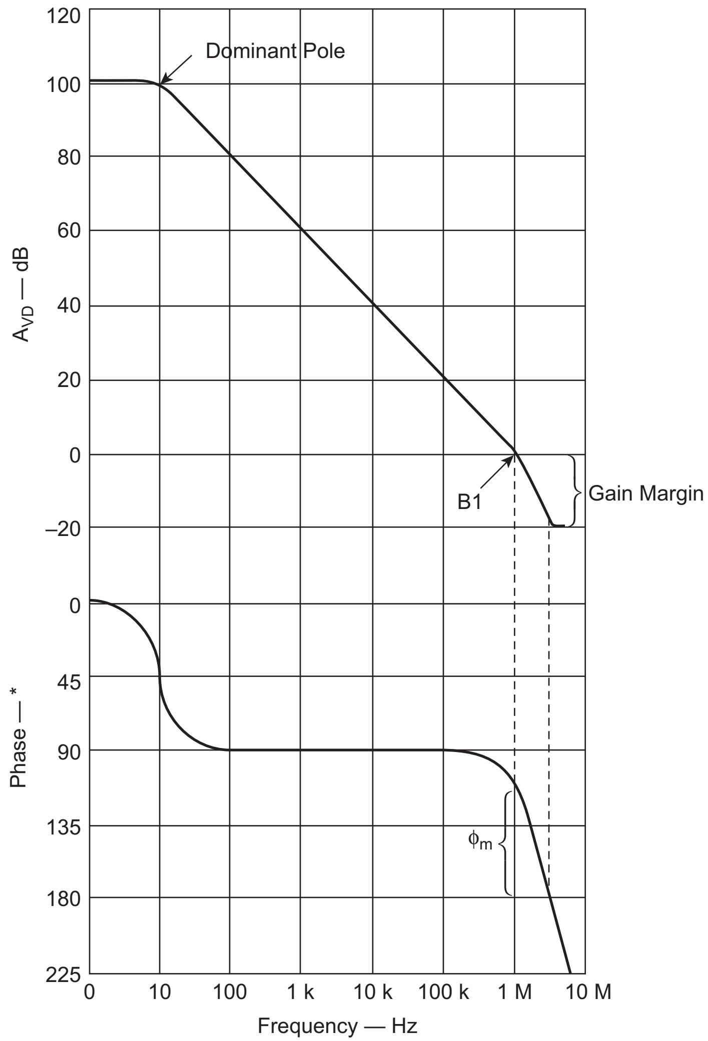

Figure B.1
Gain and phase margin.

B.6 Open-Loop Voltage Gain Parameter (A_{OL})

The open-loop voltage gain parameter, A_{OL}, is defined as the ratio of change in output voltage to the change in voltage across the input terminals. Usually, the DC value and a graph showing the frequency dependence are shown in the data sheet. It is expressed either unitless or in dB.

A_{OL} is similar to the open-loop gain A_{VD} of the amplifier except A_{VD} is usually measured with an output load. A_{OL} is usually measured without any load. Both parameters are measured open loop.

B.7 Large-Signal Voltage Amplification Gain Condition (A_V)

The large-signal voltage amplification or gain condition, A_V, is defined as the ratio of change in output voltage to the change in voltage across the input terminals that is set up for a test of parameters such as Z_O or THD + N. It is expressed either unitless or in dB.

B.8 Differential Large-Signal Voltage Amplification Parameter (A_{VD})

The differential large-signal voltage amplification parameter, A_{VD}, is defined as the ratio of change in output voltage to the change in voltage across the input terminals. It is expressed either unitless or in dB. A_{VD} is sometimes referred to as differential voltage gain. A_{VD} is similar to the open-loop gain A_{OL} of the amplifier except A_{OL} is usually measured without any load. A_{VD} is usually measured with a load. Both parameters are measured open loop.

B.9 Unity Gain Bandwidth Parameter (B_1)

Unity gain bandwidth, B_1, is defined as the range of frequencies within which the open-loop voltage amplification is greater than or equal to unity (0 dB). B_1 is expressed in units of Hertz.

B.10 Maximum-Output-Swing Bandwidth Parameter (B_{OM})

The maximum-output-swing bandwidth parameter, B_{OM}, is defined as the maximum frequency that the output swing is above a specified value or at the extents of its linear range. B_{OM} is also called full-power bandwidth. B_{OM} is expressed in units of Hertz.

The limiting factor for B_{OM} is slew rate (SR). As the frequency gets higher and higher the output becomes SR limited and cannot respond quickly enough to maintain the specified output voltage swing. The following equation expresses the relationship between B_{OM} and SR.

$$B_{OM} = \frac{SR}{2\pi V_{(PP)}} \tag{B.1}$$

B.11 Bandwidth Parameter (BW)

Bandwidth, BW, is defined as the maximum frequency that an op amp circuit can deliver the specified output. The specified output varies and includes conditions such as small signal (−3 dB), 0.1 dB flatness, and full power. BW is expressed in units of Hertz.

B.12 Input Capacitance Parameter (C_i)

The input capacitance parameter, C_i, is defined as the capacitance between the input terminals of an op amp with either input grounded. It is expressed in units of farads.

C_i is one of a group of parasitic elements affecting input impedance. Fig. B.2 shows a model of the resistance and capacitance between each input terminal and ground and between the two terminals. There is also parasitic inductance, but the effects are negligible at low frequency. Input impedance is a design issue when the source impedance is high. The input loads the source.

Input capacitance, C_i, is measured between the input terminals with either input grounded. C_i is usually a few picofarads. In the figure above, if V_p is grounded, then $C_i = C_d \| C_n$.

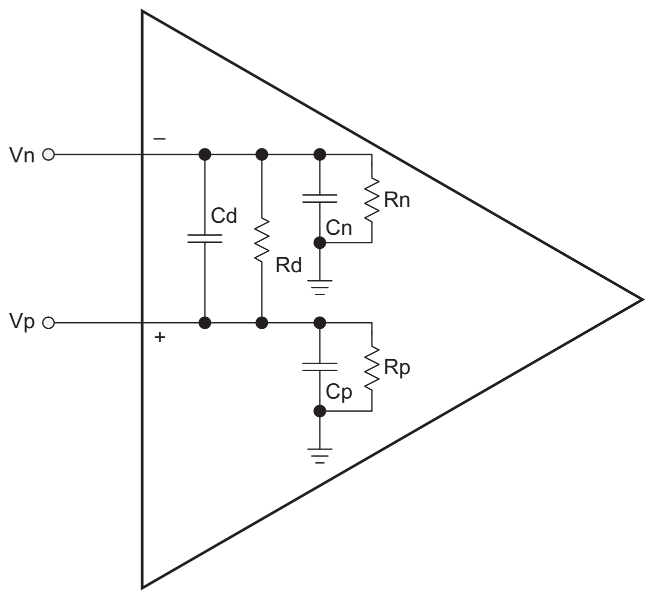

Figure B.2
Input parasitic elements.

Sometimes common-mode input capacitance, C_{ic}, is specified. In the figure above, if V_p is shorted to V_n, then $C_{ic} = C_p \| C_n$. C_{ic} is the input capacitance a common-mode source would see referenced to ground.

B.13 Common-Mode Input Capacitance Parameter (C_{ic} or $C_{i(c)}$)

The common-mode input capacitance parameter, C_{ic} or $C_{i(c)}$, is defined as the input capacitance a common-mode source would see to ground. It is expressed in units of farads.

C_{ic} is one of a group of parasitic elements affecting input impedance. Fig. B.2 shows a model of the resistance and capacitance between each input terminal and ground and between the two terminals. There is also parasitic inductance, but the effects are negligible at low frequency. Input impedance is a design issue when the source impedance is high. The input loads the source.

Input capacitance, C_i, is measured between the input terminals with either input grounded. C_i is usually a few picofarads. In the figure above, if V_p is grounded, then $C_i = C_d \| C_n$.

Sometimes common-mode input capacitance, C_{ic} is specified. In the figure above, if V_p is shorted to V_n, then $C_{ic} = C_p \| C_n$. C_{ic} is the input capacitance a common mode source would see when referenced to ground.

B.14 Differential Input Capacitance Parameter (C_{id})

The differential input capacitance parameter, C_{id}, is the same as the common-mode input capacitance, C_{id}. It is the input capacitance a common-mode source would see to ground. It is expressed in units of farads.

B.15 Load Capacitance Condition (C_L)

The load capacitance condition, C_L, is defined as the capacitance between the output terminal of an op amp and ground. It is expressed in units of farads.

C_L is a capacitive load that is sometimes connected to an op amp when parameters such as SR, t_s, Φ_m, or A_m are being tested.

B.16 Supply Voltage Sensitivity ($\Delta V_{DD\pm(or\ CC\pm)}/\Delta V_{IO}$, or k_{SVS})

The power supply rejection ratio ($\Delta V_{DD\pm(or\ CC\pm)}/\Delta V_{IO}$) is the same as the supply rejection ratio, k_{SVR}. It is defined as the absolute value of the ratio of the change in supply voltages to the resulting change in input offset voltage. Typically both supply voltages are varied symmetrically. It is expressed in dB.

The power voltage affects the bias point of the input differential pair. Because of the inherent mismatches in the input circuitry, changing the bias point changes the offset voltage, which, in turn, changes the output voltage.

For a dual-supply op amp, $k_{SVR} = \Delta V_{CC\pm}/\Delta V_{OS}$ or $\Delta V_{DD\pm}/\Delta V_{OS}$. The term $\Delta V_{CC\pm}$ means that the plus and minus power supplies are changed symmetrically. For a single-supply op amp, $k_{SVR} = \Delta V_{CC}/\Delta V_{OS}$ or $\Delta V_{DD}/\Delta V_{OS}$. Also note that the mechanism that produces k_{SVR} is the same as for common-mode rejection ratio (CMRR). Therefore k_{SVR} as published in the data sheet is a DC parameter like CMRR. When k_{SVR} is graphed versus frequency, it falls off as the frequency increases.

Switching power supplies produce noise frequencies from 50 to 500 kHz and higher. k_{SVR} is almost zero at these frequencies so that noise on the power supply results in noise on the output of the op amp.

Proper bypassing techniques must be used.

B.17 Common-Mode Rejection Ratio Parameter (CMRR or k_{CMR})

The common-mode rejection ratio parameter, CMRR or k_{CMR}, is defined as the ratio of differential voltage amplification to common-mode voltage amplification. This is measured by determining the ratio of a change in input common-mode voltage to the resulting change in input offset voltage. It is expressed in dB.

Ideally CMRR or k_{CMR} would be infinite with common-mode voltages being totally rejected.

The common-mode input voltage affects the bias point of the input differential pair. Because of the inherent mismatches in the input circuitry, changing the bias point changes the offset voltage, which, in turn, changes the output voltage. The real mechanism at work is $\Delta_{VOS}/\Delta V_{COM}$.

A common source of common-mode interference voltage is 50–60 Hz AC noise. Care must be used to ensure that the CMRR of the op amp is not degraded by other circuit components. High values of resistance make the circuit vulnerable to common-mode (and other) noise pick up. It is usually possible to scale resistors down and capacitors up to preserve circuit response.

B.18 Frequency Condition (f)

Frequency condition, f, is the frequency available to a circuit for a specific parameter test. It is expressed in Hertz.

B.19 Op Amp Gain Bandwidth Product Parameter (GBW)

Gain bandwidth product, GBW, is defined as the product of the open-loop voltage gain and the frequency at which it is measured. GBW is expressed in units of Hertz. Fig. B.1 shows the open-loop bandwidth graphically.

GBW is similar to unity-gain bandwidth (B_1). While B_1 specifies the frequency at which the gain of the op amp is 1, GBW specifies the gain-bandwidth product of the op amp at a frequency that may be different than the B_1.

GBW is constant for voltage-feedback amplifiers. It does not have much meaning for current-feedback amplifiers because there is not a linear relationship between gain and bandwidth.

When an op amp is selected for a specific application both the bandwidth and the SR should be taken into account (along with other factors including power consumption, distortion, price, etc.).

B.20 Supply Current (Shutdown) Parameter ($I_{CC(SHDN)}$ or $I_{DD(SHDN)}$)

The supply current (shutdown) parameter, $I_{CC(SHDN)}$ or $I_{DD(SHDN)}$, is defined as the current into the V_{CC+} (V_{DD+}) or V_{CC-} (V_{DD-}) terminal of the amplifier while it is turned off. It is expressed in units of amperes.

B.21 Supply Current Parameter (I_{CC} or I_{DD})

The supply current parameter, I_{CC} or I_{DD}, is defined as the current into the V_{CC+} (V_{DD+}) or V_{CC-} (V_{DD-}) terminal of the op amp while it is operating without load and the input and/or output is at virtual ground. It is expressed in units of amperes.

B.22 Input Current Range Parameter (I_I)

The input current range parameter, I_I, is defined as the amount of current that can be sourced or sinked by the op amp input. It is usually specified as an absolute maximum rating expressed in units of amperes.

B.23 Input Bias Current Parameter (I_{IB})

The input bias current parameter, I_{IB}, is defined as the average of the currents into the two input terminals with the output at a specified level. It is expressed in units of amperes.

The input circuitry of all op amps requires a certain amount of bias current for proper operation. The input bias current, I_{IB}, is computed as the average of the two inputs:

$$I_{IB} = \frac{(I_N + I_P)}{2} \tag{B.2}$$

CMOS and JFET inputs offer much lower input current than standard bipolar inputs.

Input bias current is of concern when the source impedance is high. If the op amp has high input bias current, it will load the source and a lower than expected voltage is seen. If the source impedance is high, the best solution is to use an op amp with either CMOS or JFET input. The source impedance can also be lowered by using a buffer stage to drive the op amp that has high input bias current.

B.24 Input Offset Current Parameter (I_{IO})

The input offset current parameter, I_{IO}, is defined as the difference between the currents into the two input terminals of an op amp with the output at the specified level. It is expressed in units of amperes.

B.25 Input Noise Current Parameter (I_n)

The input noise current parameter, I_n, is defined as the internal noise current reflected back to an ideal current source in parallel with the input pins. It is expressed in units of $A/\sqrt{Hz}$.

It is important for a designer to calculate noise that the device will deliver in an application. The simplest way is to calculate this noise is to use the following equation:

$$e_{nt} = \sqrt{V_n{}^2 + (I_n \times R_s)^2} \tag{B.3}$$

where, e_{nt} = total noise voltage; V_n = voltage noise ($nV/\sqrt{Hz}$); I_n = current noise ($pA/\sqrt{Hz}$); R_s = source resistance (Ω).

B.26 Output Current Parameter (I_O)

The output current parameter, I_O, is defined as the amount of current that may be drawn from the op amp output. Usually I_O is expressed in units of amperes.

B.27 Low-level Output Current Condition (I_{OL})

The low-level output current condition, I_{OL}, is defined as the current into an output that is supplied during the test for V_{OL}. It is usually expressed in units of amperes.

B.28 Short-Circuit Output Current Parameters (I_{OS} or I_{SC})

The short-circuit output current parameter, I_{OS} or I_{SC}, is defined as the maximum output current available from the amplifier with the output shorted to ground, to either supply, or to a specified point. Sometimes a low-value series resistor is specified. It is usually expressed in units of amperes.

It is important to observe power dissipation ratings to keep the junction temperature below the absolute maximum rating when the output is heavily loaded or shorted. See the absolute maximum ratings section of the part's data sheet for more information.

B.29 Supply Rejection Ratio Parameter (k_{SVR})

The supply rejection ratio, k_{SVR}, is the same as the power supply rejection ratio, PSRR. It is defined as the absolute value of the ratio of the change in supply voltages to the resulting change in input offset voltage. Typically both supply voltages are varied symmetrically. It is expressed in dB.

The power voltage affects the bias point of the input differential pair. Because of the inherent mismatches in the input circuitry, changing the bias point changes the offset voltage, which, in turn, changes the output voltage.

For a dual-supply op amp, $k_{SVR} = \Delta V_{CC\pm}/\Delta V_{OS}$ or $\Delta V_{DD\pm}/\Delta V_{OS}$. The term $\Delta V_{CC\pm}$ means that the plus and minus power supplies are changed symmetrically. For a single-supply op amp, $k_{SVR} = \Delta V_{CC}/\Delta V_{OS}$ or $\Delta V_{DD}/\Delta V_{OS}$. Also note that the mechanism that produces k_{SVR} is the same as for CMRR. Therefore k_{SVR} as published in the data sheet is a DC parameter like CMRR. When k_{SVR} is graphed versus frequency, it falls off as the frequency increases.

Switching power supplies produce noise frequencies from 50 to 500 kHz and higher. k_{SVR} is almost zero at these frequencies so that noise on the power supply results in noise on the output of the op amp.

Proper bypassing techniques must be used.

B.30 Power Dissipation Parameter (P_D)

The power dissipation, P_D, is defined as the power supplied to the device less any power delivered from the device to a load. Note: At no load: $P_D = V_{CC+} \times I_{CC}$ or $P_D = V_{DD+} \times I_{DD}$. It is expressed in units of Watts.

B.31 Power Supply Rejection Ratio Parameter (PSRR)

The power supply rejection ratio, PSRR, is the same as the supply rejection ratio, k_{SVR}—see Section B.28.

B.32 Junction to Ambient Thermal Resistance Parameter (θ_{JA})

The junction to ambient thermal resistance parameter, θ_{JA}, is defined as the ratio of the difference in temperature from the die junction to the ambient air and the power dissipated by the die. θ_{JA} is expressed in units of °C/W.

θ_{JA} is dependent on the case to the ambient thermal resistance as well as the θ_{JC} parameter. θ_{JA} is a better indicator of thermal resistance when the package is not well thermally sinked to other components in the assembly. θ_{JA} is listed in the data sheet for different packages. It is useful for evaluating which package is least likely to overheat and to determine what the die temperature is when the ambient temperature and power dissipation are known.

B.33 Junction to Case Thermal Resistance Parameter (θ_{JC})

The junction to case thermal resistance parameter, θ_{JC}, is defined as the ratio of the difference in temperature from the die junction to the case and the power dissipated by the die. θ_{JC} is expressed in units of °C/W.

θ_{JC} is not dependent on the case to the ambient thermal resistance as is the θ_{JA} parameter. θ_{JC} is a better indicator of thermal resistance when the package is to be thermally sinked to other components in the assembly.

θ_{JC} is listed in the data sheet for different packages. It is useful for evaluating which package is least likely to overheat and to determine what the die temperature is when the case temperature and power dissipation are known.

B.34 Input Resistance Parameter (r_i)

The input resistance parameter, r_i, is defined as the DC resistance between the input terminals with either input grounded. It is expressed in units of Ω.

r_i is one of a group of parasitic elements affecting input impedance. Fig. B.2 shows a model of the resistance and capacitance between each input terminal and ground and between the two terminals. There is also parasitic inductance, but the effects are negligible at low frequency. Input impedance is a design issue when the source impedance is high. The input loads the source.

Input resistance, r_i, is the resistance between the input terminals with either input grounded. In the figure above, if V_p is grounded, then $r_i = R_d||R_n$. r_i ranges from 10^7 to 10^{12} Ω, depending on the type of input.

Sometimes common-mode input resistance, r_{ic}, is specified. In the figure above, if V_p is shorted to V_n, then $r_{ic} = R_p||R_n$. r_{ic} is the input resistance a common-mode source would see referenced to ground.

B.35 Differential Input Resistance Parameter (r_{id} or $r_{i(d)}$)

The differential input resistance, r_{id} or $r_{i(d)}$, is defined as the small-signal resistance between two ungrounded input terminals. It is expressed in units of Ω.

r_{id} is one of a group of parasitic elements affecting input impedance. Fig. B.2 shows a model of the resistance and capacitance between each input terminal and ground and between the two terminals. There is also parasitic inductance, but the effects are negligible at low frequency. Input impedance is a design issue when the source impedance is high. The input loads the source.

Input resistance, r_i, is the resistance between the input terminals with either input grounded. In the figure above, if V_p is grounded, then $r_i = R_d||R_n$. r_i ranges from 10^7 to 10^{12} Ω, depending on the type of input.

Sometimes common-mode input resistance, r_{ic}, is specified. In the figure above, if V_p is shorted to V_n, then $r_{ic} = R_p||R_n$. r_{ic} is the input resistance a common mode source would see referenced to ground. In Fig. B.2, $r_{id} = R_d$.

B.36 Load Resistance Condition (R_L)

The load resistance condition, R_L, is defined as the DC resistance that is attached from the output of an op amp to ground during a test for a parameter such as A_{VD}, SR, THD + D, $t_{(on)}$, $t_{(off)}$, GBW, t_s, Φ_m, and A_m. It is expressed in units of Ω.

B.37 Null Resistance Condition (R_L)

The null resistance condition, R_L, is defined as the DC resistance that is attached in series with C_L when testing for parameters such as phase margin and gain margin. It is expressed in units of Ω.

B.38 Output Resistance Parameters (r_o)

The output resistance parameter, r_o, is defined as the DC resistance that is placed in series with the output of an ideal amplifier and the output terminal for simulation of the real device. It is expressed in units of Ω.

B.39 Signal Source Condition (R_S)

The signal source condition, R_S, is defined as the output resistance of a signal source. It is expressed in units of Ω. R_S is used as a test condition when measuring parameters such as V_{IO}, α_{VIO}, I_{IO}, I_{IB}, and CMMR. A typical value for R_S used in these parameter tests is 50 Ω.

B.40 Open-Loop Transresistance Parameters (R_t)

In a transimpedance or current-feedback amplifier, the open-loop transresistance parameter, R_t is defined as the ratio of change in DC output voltage to the change in DC current at the inverting input. It is expressed in units of Ω.

B.41 Op Amp Slew Rate Parameter (SR)

The slew rate parameter, SR, is defined as the rate of change in the output voltage caused by a step change at the input. It is expressed in V/s. The SR parameter of an op amp is the maximum SR it will pass and is generally specified with a gain of 1. Fig. B.3 shows SR graphically.

For an amplifier to pass a signal without distortion due to insufficient SR, the amplifier must have at least the maximum SR of the signal. The maximum SR of a sine wave occurs as it crosses zero. The following equation defines this SR:

$$SR = 2\pi fV \tag{B.4}$$

where, f = frequency of the signal; V = peak voltage of the signal.

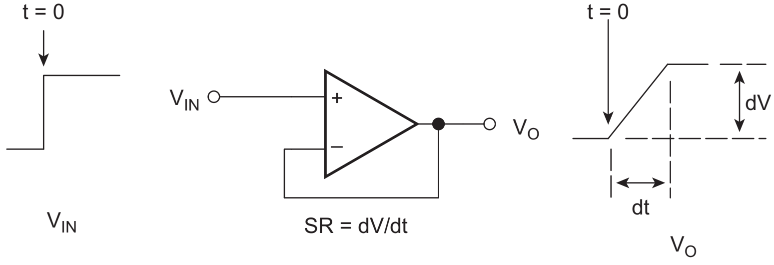

Figure B.3
Slew rate.

The SR is sometimes represented as SR+ and SR−. SR+ is the abbreviation for the SR for a positive transition, and SR− is the abbreviation for the SR for a negative transition. Many applications are best served when SR+ and SR− are the same magnitude.

The primary factor controlling SR in most op amps is an internal compensation capacitor, which is added to make the op amp unity gain stable. When an op amp is selected for a specific application both the bandwidth and the SR should be taken into account.

B.42 Operating Free-Air Temperature Condition (T_A)

The operating free-air temperature condition, T_A, is defined as the free-air temperature over which the op amp is being operated. Some of the other parameters may change with temperature, leading to degraded operation at temperature extremes. T_A is expressed in units of °C.

A range of T_A is listed in a data sheet's absolute maximum ratings table because stress beyond those listed may cause permanent damage to the device. Functional operation to this limit is not implied and may affect reliability.

B.43 Turn-Off Time (Shutdown) Parameter (t_{DIS} or $t_{(off)}$)

The turn-off time (shutdown) parameter, t_{DIS} or $t_{(off)}$, is defined as the time from when the turn-off voltage is applied to the shutdown pin to when the supply current has reached half of its final value. It is expressed in units of seconds.

B.44 Turn-On Time (Shutdown) Parameters (t_{EN})

The turn-on time (shutdown) parameter, t_{EN}, is defined as the time from when the turn-on voltage is applied to the shutdown pin to when the supply current has reached half of its final value. It is expressed in units of seconds.

B.45 Fall Time Parameter (t_f)

The fall time parameter, t_f, is defined as the time required for an output voltage step to change from 90% to 10% of its final value. It is expressed in units of seconds.

B.46 Total Harmonic Distortion Parameter (THD)

The total harmonic distortion parameter, THD, is defined as the ratio of the RMS voltage of the harmonics of the fundamental signal to the total RMS voltage at the output. THD is expressed in dBc or %. THD does not account for the noise as does the total harmonic distortion plus noise parameter.

B.47 Total Harmonic Distortion Plus Noise Parameter (THD + N)

The total harmonic distortion plus noise parameter, THD + N, is defined as the ratio of the RMS noise voltage plus the RMS harmonic voltage of the fundamental signal to the fundamental RMS voltage signal at the output. It is expressed in dBc or %.

THD + N compares the frequency content of the output signal to the frequency content of the input. Ideally, if the input signal is a pure sine wave, the output signal is a pure sine wave. Due to nonlinearity and noise sources within the op amp, the output is never pure.

To simplify further, THD + N is the ratio of all other frequency components to the fundamental.

$$\mathrm{THD}+\mathrm{N}=\left[\frac{(\sum \text{Harmonic voltages}+\text{Noise voltages})}{\text{Fundamental}}\right]\times 100\% \qquad \text{(B.5)}$$

B.48 Maximum Junction Temperature Parameter (T_J)

The maximum junction temperature parameter, T_J, is defined as the temperature over which the die may be operated. Some of the other parameters may change with temperature, leading to degraded operation at temperature extremes. T_J is expressed in units of °C.

T_J is listed in the absolute maximum ratings table because stress beyond those listed may cause permanent damage to the device. Functional operation to this limit is not implied and may affect reliability.

B.49 Rise Time Parameter (t_r)

The rise time parameter, t_r, is defined as the time required for an output voltage step to change from 10% to 90% of its final value. It is expressed in units of seconds.

B.50 Settling Time Parameter (t_s)

The settling time parameter, t_s, is defined as the time required for the output voltage to settle within the specified error band of the final value with a step change at the input. It is also known as total response time, t_{tot}. It is expressed in units of seconds.

Settling time is greatly affected by the application, such as a filter circuit where capacitors can store energy. Therefore, it should be measured in-circuit. It is particularly a design issue in data acquisition circuits when signals are changing rapidly. An example is when using an op amp following a multiplexer to buffer the input to an A to D converter. Step changes can occur at the input to the op amp when the multiplexer changes channels. The output of the op amp must settle to within a certain tolerance before the A to D converter samples the signal.

B.51 Storage Temperature Parameter (T_S or T_{stg})

The storage temperature parameter, T_S or T_{stg}, is defined as the temperature over which the op amp may be stored (unpowered) for long periods of time without damage. It is expressed in units of °C.

B.52 Supply Voltage Condition (V_{CC} or V_{DD})

The supply voltage condition, V_{CC} or V_{DD}, is defined as the bias voltage applied to the op amp power supply pin(s). For single-supply applications, it is specified as a positive value; and for split-supply applications, it is specified as a ± value, referenced to analog ground. It is expressed in units of volts.

V_{CC} or V_{DD} is often defined in the maximum ratings, recommended operating conditions and as a test condition in parameter tables and graphs because the voltage supplied has an important impact on the way a circuit operates. It is also used as one of the axis variables in some of the characteristic graphs.

B.53 Input Voltage Range Condition or Parameter (V_I)

The input voltage range parameter, V_I, is defined as the range of input voltages that may be applied to either the IN+ or IN− inputs. The input voltage range condition, V_I, is defined as the voltage delivered to a circuit input when testing for V_O on a graph such as "large signal inverting pulse response versus time." V_I is expressed in units of volts for either a condition or parameter.

B.54 Common-Mode Input Voltage Condition (V_{ic})

The common-mode input voltage condition, V_{ic}, is defined as the voltage that is common to both input pins. V_{ic} as expressed in units of volts, V. V_{io} set at $V_{DD}/2$ (for single-supply op amps) is often used as a condition when testing for various parameters including V_{IO}, I_{IO}, I_{IB}, V_{OH}, and V_{OL}.

When a two-wire signal is subject to noise and this noise is being received equally on both signal lines, then it can be rejected by a differential amplifier with good common-mode rejection.

B.55 Common-Mode Input Voltage Range Parameter (V_{ICR})

The common-mode input voltage range parameter, V_{ICR}, is defined as the range of common-mode input voltage that, if exceeded, may cause the operational amplifier to cease functioning properly. This sometimes is taken as the voltage range over which the input offset voltage remains within a set limit. V_{ICR} is expressed in units of volts.

The input common voltage, V_{IC}, is defined as the average voltage at the inverting and noninverting input pins. If the common-mode voltage gets too high or too low, the inputs will shut down and proper operation ceases. The common-mode input voltage range, V_{ICR}, specifies the range over which normal operation is guaranteed. The trends toward lower and single-supply voltages make V_{ICR} of increasing concern.

Rail-to-rail input is required when a noninverting unity gain amplifier is used and the input signal ranges between both power rails. An example of this is the input of an analog to digital converter in a low-voltage, single-supply system.

High-side sensing circuits require operation at the positive input rail.

B.56 Differential Input Voltage Parameter (V_{ID})

The differential input voltage parameter, V_{ID}, is defined as the voltage at the noninverting input with respect to the inverting input. V_{ID} is expressed in units of volts.

V_{ID} is usually defined in the absolute maximum ratings table because stress beyond this limit may cause permanent damage to the device.

B.57 Differential Input Voltage Range Parameter (V_{DIR})

The input common-mode voltage range parameter, V_{DIR}, is defined as the range of differential input voltage that, if exceeded, may cause the operational amplifier to cease functioning properly. V_{DIR} is expressed in units of volts.

Some devices have protection built into them, and the current into the input needs to be limited. Normally, differential input mode voltage limit is not a design issue.

B.58 Turn-on Voltage (Shutdown) Parameter ($V_{IH\text{-}SHDN}$ or $V_{(ON)}$)

The turn-on voltage (shutdown) parameter, $V_{IH\text{-}SHDN}$ or $V_{(ON)}$, is defined as the voltage required on the shutdown pin to turn the device on. It is expressed in units of volts.

B.59 Turn-off Voltage (Shutdown) Parameters ($V_{IL\text{-}SHDN}$ or $V_{(OFF)}$)

The turn-off voltage (shutdown) parameter, $V_{IL\text{-}SHDN}$ or $V_{(OFF)}$, is defined as the voltage required on the shutdown pin to turn the device off. It is expressed in units of volts.

B.60 Input Voltage Condition (V_{IN})

The input voltage condition, V_{IN}, is defined as the DC voltage delivered to a circuit input when testing for V_n. V_I is expressed in units of volts.

B.61 Input Offset Voltage Parameter (V_{IO} or V_{OS})

The input offset voltage parameter, V_{IO} or V_{OS}, is defined as the DC voltage that must be applied between the input terminals to cancel DC offsets within the op amp. It is expressed in units of volts.

All op amps require a small voltage between their inverting and noninverting inputs to balance mismatches due to unavoidable process variations. The required voltage is known as the input offset voltage and is abbreviated V_{IO}. V_{IO} is an input referred parameter. This means that it is amplified by the positive closed-loop gain of the circuit.

Input offset voltage is of concern anytime that DC accuracy is required of the circuit. One way to null the offset is to use external null inputs on a single op amp package (Fig. B.4). A potentiometer is connected between the null inputs with the adjustable terminal

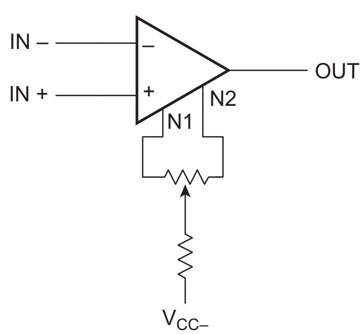

Figure B.4
Offset voltage adjust.

connected to the negative supply through a series resistor. The input offset voltage is nulled by shorting the inputs and adjusting the potentiometer until the output is zero.

B.62 Equivalent Input Noise Voltage Parameter (V_n)

The equivalent input noise voltage parameter, V_n, is defined as the internal noise voltage reflected back to an ideal voltage source in parallel with the input pins at a specific frequency. V_n is expressed in units of $V/\sqrt{Hz}$.

When this parameter is measured, the noise measured at the output (with the input connected to virtual ground) is divided by the gain of the amplifier circuit. This is the amplitude of noise at the input that would be amplified by an ideal amplifier to cause an equivalent signal at the output.

V_n is sometimes defined at several frequencies in the operating characteristics table or as a graph.

B.63 High-Level Output Voltage Condition or Parameter (V_{OH})

The high-level output voltage parameter, V_{OH}, is defined as the positive rail of the op amp output for the load current conditions applied to the power pins. When the V_{OH} parameter is tested, it may be defined with I_{OH} of −1, −20, −35, and −50 mA load. When V_{OH} is listed on a data sheet as a test condition, it is used for testing another parameter. Whether V_{OH} is a condition or a parameter it is expressed in units of volts.

B.64 Low-Level Output Voltage Condition or Parameter (V_{OL})

The low-level output voltage parameter, V_{OL}, is defined as the negative rail of the op amp output for the load current conditions applied to the power pins. When the V_{OL} parameter is tested, it may be defined with I_{OL} of −1, −20, −35, and −50 mA load. When V_{OL} is listed on a data sheet as a test condition, it is used for testing another parameter. Whether V_{OL} is a condition or parameter it is expressed in units of volts.

B.65 Maximum Peak-to-Peak Output Voltage Swing Parameter ($V_{OM\pm}$)

The maximum peak-to-peak output voltage swing parameter, $V_{OM\pm}$, is defined as the maximum peak-to-peak output voltage that can be obtained without clipping when the op amp is operated from a bipolar supply. $V_{OM\pm}$ is expressed in units of volts.

B.66 Peak-to-Peak Output Voltage Swing Condition or Parameter ($V_{O(PP)}$)

The peak-to-peak output voltage swing condition, $V_{O(PP)}$, is defined as the peak-to-peak voltage set up on the output waveform to test for parameters such as A_{VD} or SR.

The peak-to-peak output voltage swing parameter, $V_{O(PP)}$, is the maximum peak-to-peak output voltage that an op amp can deliver. When it is measured V_{DD}, THD + H, R_L and T_A are the typical test conditions.

$V_{O(PP)}$ is also expressed in units of volts for either a condition or parameter.

B.67 Step Voltage Peak-to-Peak Condition ($V_{(STEP)PP}$)

The step voltage peak-to-peak condition, $V_{(STEP)PP}$, is defined as the peak-to-peak voltage step that is used as a test condition for parameters such as t_s. $V_{(STEP)PP}$ is expressed in units of volts.

B.68 Crosstalk Parameter (X_T)

The crosstalk parameter, X_T, is defined as the ratio of the change in output voltage of a driven channel to the resulting change in output voltage from another channel that is not driven. X_T is expressed in units of dB.

X_T is a function of how good the separation is between channels in an IC package or system. It is caused by the signal from one channel being coupled to the other channel inductively, capacitively, through the power supply, etc.

B.69 Output Impedance Parameter (Z_O)

The output impedance parameter, Z_O, is defined as the frequency-dependent small-signal impedance that is placed in series with an ideal amplifier and the output terminal in a closed-loop configuration. Z_O is expressed in units of Ω.

B.70 Open-Loop Transimpedance Parameter (Z_t)

The open-loop transimpedance parameter, Z_t, is defined as the frequency-dependent ratio of change in output voltage to the frequency-dependent change in current at the inverting input in a transimpedance or current-feedback amplifier. Z_t is expressed in units of Ω.

B.71 Differential Phase Error Parameter (Φ_D)

The differential phase error parameter, Φ_D, is defined as the change in AC phase with change in DC level. The AC signal is 40 IRE (0.28 VPK) and the DC level change is $\pm$100 IRE ($\pm$0.7 V). It is typically tested at 3.58 MHz (NTSC) or 4.43 MHz (PAL) carrier frequencies. Φ_D is expressed in units of degrees. With the advent of digital television transmission, the importance of this parameter may decline.

B.72 Phase Margin Parameter (Φ_m)

The phase margin parameter, Φ_m, is defined as the absolute value of the difference in the phase shift of 180 degrees and the phase shift at unity gain. Φ_m is measured open loop and is expressed in units of degrees, °.

$$\Phi_m = 180^\circ - \Phi@B1 \tag{B.6}$$

Gain margin (A_m) and phase margin (Φ_m) are different ways of specifying the stability of the circuit. Since rail-to-rail output op amps have higher output impedance, a significant phase shift is seen when driving capacitive loads. This extra phase shift erodes the phase margin, and for this reason most CMOS op amps with rail-to-rail outputs have limited ability to drive capacitive loads. Fig. B.1 shows Φ_m graphically.

B.73 Bandwidth for 0.1 dB Flatness

Bandwidth for 0.1 dB flatness is defined as the range of frequencies within which the gain is $\pm$0.1 dB of the nominal value with full output power. It is expressed in units of Hertz.

B.74 Case Temperature for 60 s

The case temperature for 60 s is defined as the temperature the case may safely be exposed to for 60 s. It is usually specified as an absolute maximum and is meant as a guide for automated soldering processes. It is expressed in °C.

B.75 Continuous Total Dissipation Parameter

The continuous total dissipation parameter is defined as the power that can be dissipated by an op amp package, including loads. It is usually specified as an absolute maximum. This parameter may be broken down by ambient temperature and package style in a table. Continuous total dissipation is expressed in units of Watts.

B.76 Duration of Short-Circuit Current

The duration of short-circuit current parameter is defined as the amount of time that the output can be shorted to network ground. It is usually specified as an absolute maximum. Duration of short-circuit current is usually expressed in seconds.

B.77 Input Offset Voltage Long-Term Drift Parameter

Input offset voltage long-term drift parameter is defined as the ratio of the change in input offset voltage to the change in time. It is the average value for the month and is expressed in units of volts/month.

B.78 Lead Temperature for 10 or 60 s

The lead temperature for 10 or 60 s is defined as the temperature the leads may safely be exposed for 10 or 60 s. It is usually specified as an absolute maximum and is meant as a guide for automated soldering processes. This parameter is expressed in units of °C.