e-Learning

Basics of Op-amps

Chapter2 Using an op-amp

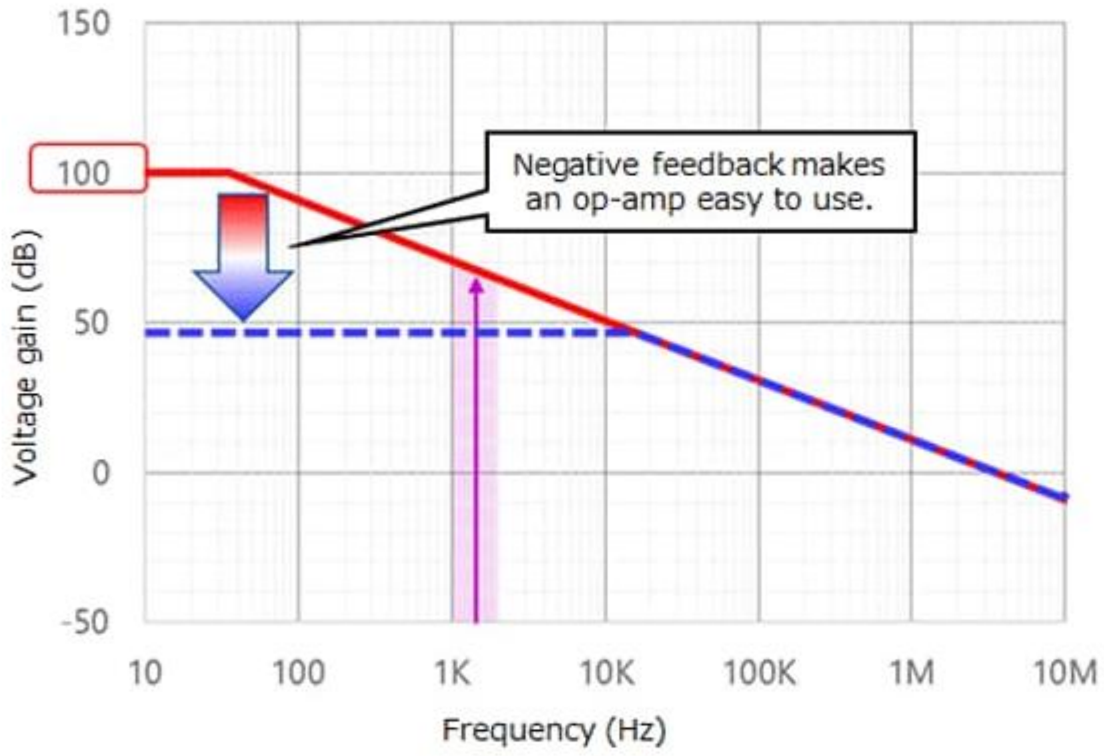
Toshiba Electronic Devices & Storage Corporation

Chapter2 Using an op-amp

Using an op-amp

An op-amp has a high gain as shown in Figure. The gain is dependent on frequency. The gain also varies from device to device and is affected by temperature and other environmental conditions. Therefore, op-amps are generally used with negative feedback. Depending on conditions, negative feedback turns into positive feedback, causing the feedback loop to oscillate abnormally.
Section 2 describes feedback oscillation, basic amplifier circuits using an op-amp, a virtual short-circuit required when considering an amplifier circuit.

1. Feedback (positive and negative feedback)
2. Open-loop gain and closed-loop gain
3. Oscillation
4. Basic amplifier circuits
5. Virtual short-circuit (virtual ground)



1. Feedback (positive and negative feedback)

Op-amps are generally used with negative feedback.
This section briefly describes negative feedback. There are two types of feedback loops: positive and negative.
For example, positive feedback can be compared to the following cycle:

1) You study hard, and your grades improve.
2) As your grades improve, studying becomes more enjoyable, and you study more.
3) Your grades improve further.

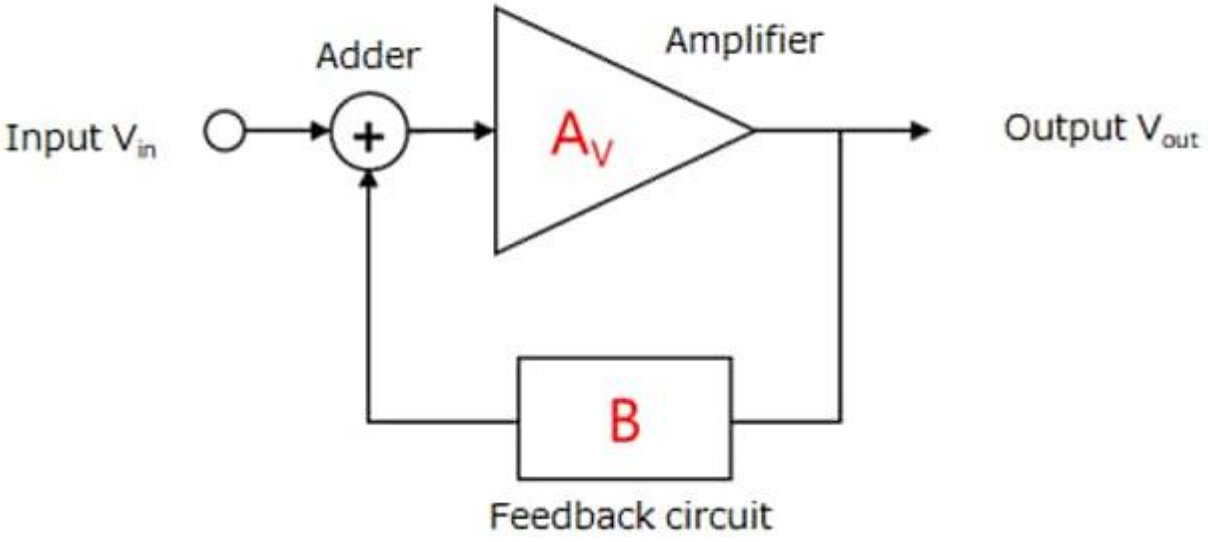
In other words, positive feedback is a process that further increases the effects of a small change in output.
In contrast, negative feedback can be compared to the following cycle:

1) You study hard, and your grades improve.
2) You spend less time studying and more time relaxing.
3) Your grades drop.
4) You spend less time relaxing and more time studying.
5) Your grades get back to the previous level.

It is a process of trying to keep the results (i.e., your grades in this example) constant. This process is called negative feedback.

1. Feedback (positive and negative feedback)

Figure shows an amplifier circuit with feedback. It consists of an amplifier, a feedback circuit, and an adder (or a subtractor). A_V is the open-loop gain of the amplifier, and B is the feedback factor.



The amplifier amplifies the input signal and outputs an amplified signal. Part of the output is returned to the input of the amplifier via the feedback circuit and the adder.
When V_{in} changes, negative feedback changes the input to the amplifier in order to counteract the effect of the change in V_{in}.
Conversely, positive feedback increases the effects of the change in V_{in}.

1. Feedback (positive and negative feedback)

The output (V_{out}) is equal to the sum of the V_{in} and feedback signals multiplied by the open-loop gain of the amplifier:

$$V_{out} = A_V \times (V_{in} + B \times V_{out})$$

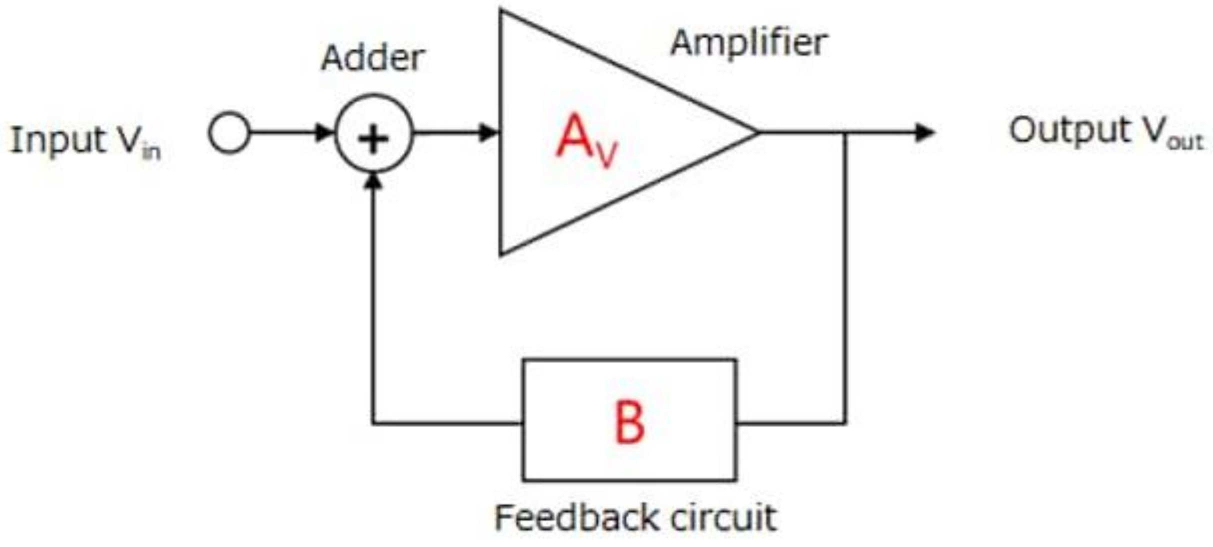
This can be rewritten as:

$$V_{out} = A_V \times V_{in} / (1 - A_V \times B)$$

If the feedback signal ($A_V \times B \times V_{out}$) has the same phase as the V_{IN} signal, the amplifier circuit has positive feedback. If the feedback signal has the opposite phase to the V_{IN} signal, the amplifier circuit has negative feedback.

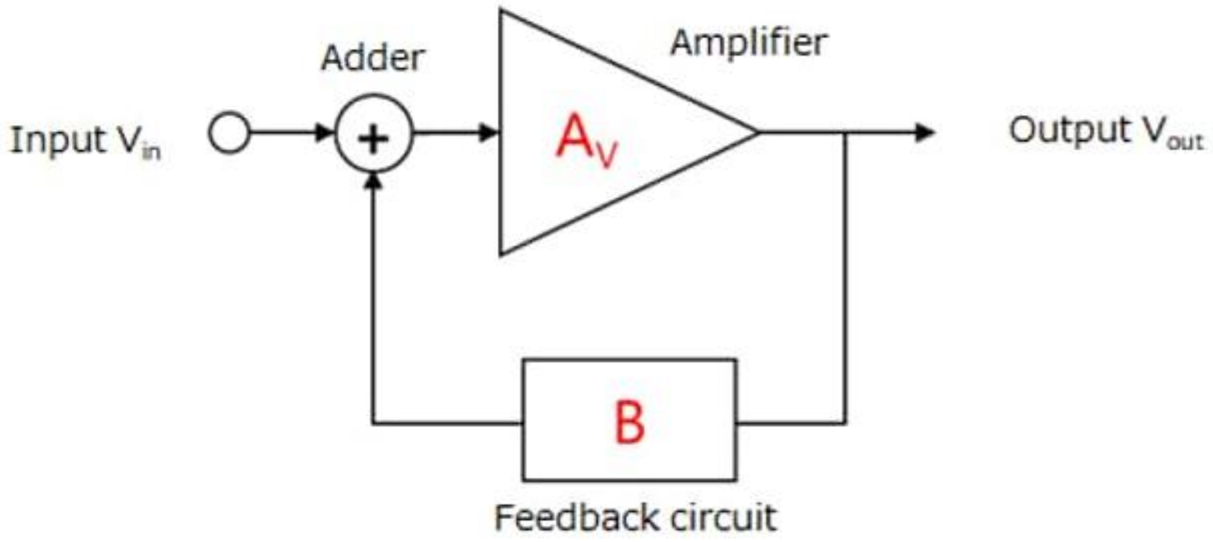
Positive feedback: $V_{out} = A_V \times V_{in} / (1 - | A_V \times B |)$

Negative feedback: $V_{out} = A_V \times V_{in} / (1 + | A_V \times B |)$



1. Feedback (positive and negative feedback)

Although an op-amp has a very high open-loop gain, it is difficult to use because of its frequency dependence (see next section). Therefore, an op-amp is generally used with negative feedback. Negative feedback causes its gain to decrease substantially. On the other hand, negative feedback increases the frequency bandwidth in which the gain curve remains flat and decreases the output impedance. In addition, negative feedback makes it possible to create an easy-to-handle amplifier because it compensates for variations in gain.
Normally, positive feedback is not used for amplifiers. For example, positive feedback is used to provide hysteresis for oscillators and comparators.
(If you are interested in this, see the FAQ entry: “How can I provide hysteresis (Schmitt trigger) for a comparator?”)



2. Open-loop and closed-loop gains (Increasing the bandwidth of an amplifier)

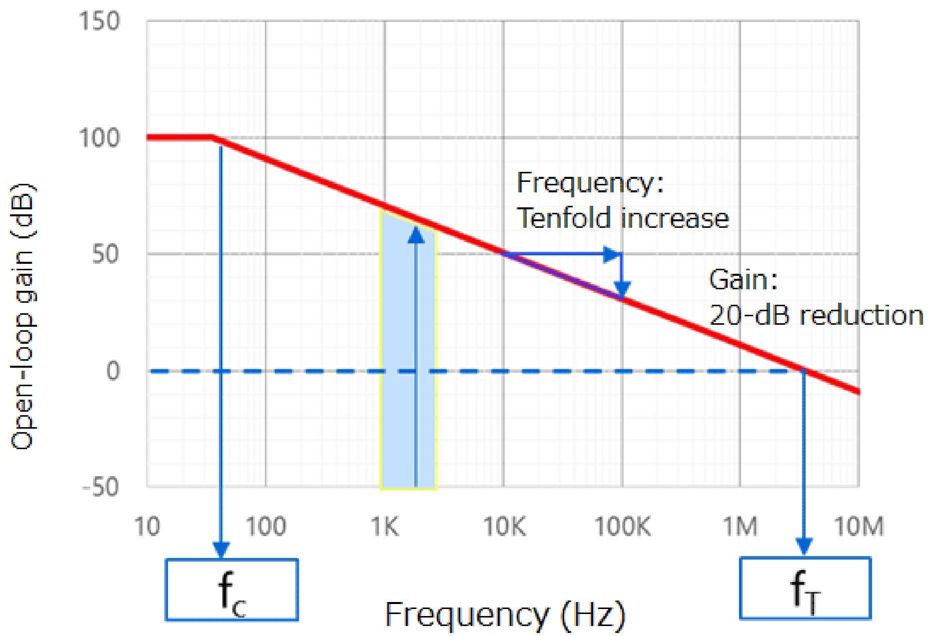
The open-loop gain (G_V) of an op-amp has the same frequency characteristics as a first-order RC lowpass filter as shown in Figure. At frequencies higher than the corner frequency (f_C) at which the open-loop gain is 3 dB lower than the DC gain, the open-loop gain decreases at a rate of 6 dB per octave (20 dB per decade). In this frequency range, the decibel open-loop gain of the op-amp (G_V) decreases by 6 dB (i.e., the linear open-loop gain (A_V) halves) when the frequency doubles. Hence:

$$f_c \times A_V = \text{constant}$$

The frequency at which the gain is equal to 1 (0 dB) is called the unity gain cross frequency (f_T). Therefore, the above equation can be restated as follows. This is called the gain-bandwidth product (designated as GBWP, GBW, GBP, or GB).

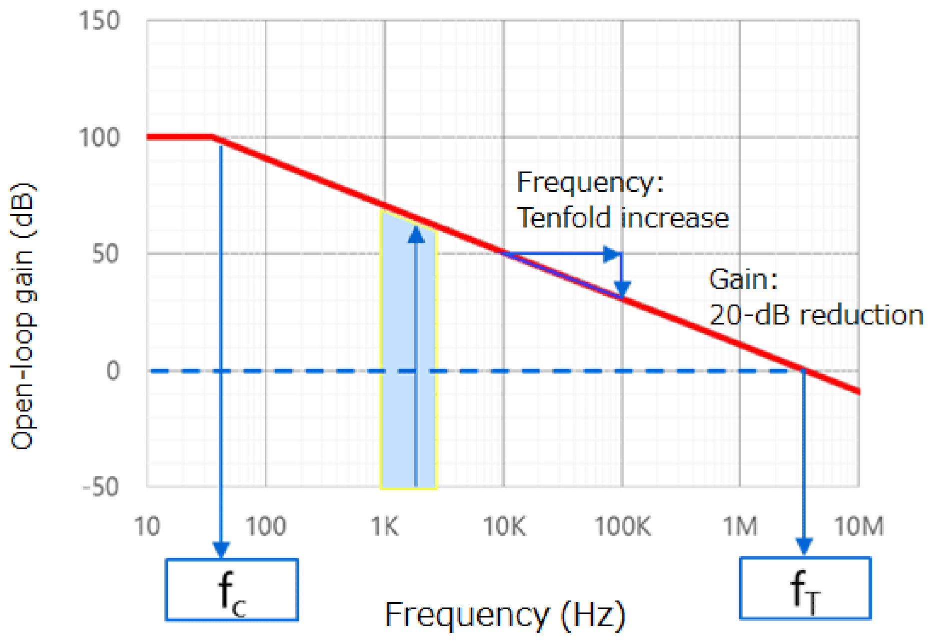
$$f_c \times A_V = f_T$$

Note that this equation is true in the frequency range in which the open-loop gain decreases at a rate of 6 dB per octave.



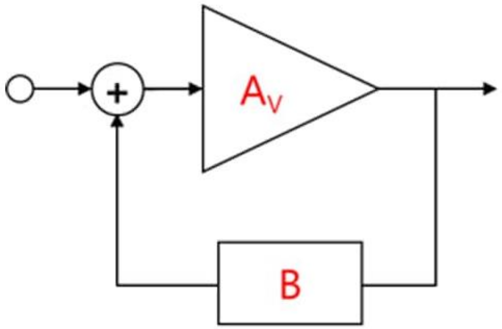
2. Open-loop and closed-loop gains (Increasing the bandwidth of an amplifier)

Now, let’s consider what occurs when an input signal with a frequency of 2±1 kHz is applied to an op-amp that has frequency characteristics as shown in Figure. In the case of an op-amp under this condition, the gain at 3 kHz is roughly 10 dB lower than the gain at 1 kHz. Normally, the op-amp cannot be used under this condition. Negative feedback solves this issue.



2. Open-loop and closed-loop gains (Increasing the bandwidth of an amplifier)

As mentioned in the previous section, when an op-amp is used as an amplifier, it is usually used with negative feedback. The figure shows an amplifier circuit with feedback.



The input (V_{in}) and the output (V_{out}) have the following relationship. This relationship is called a closed-loop gain (represented as G_{CL} in dB scale and A_{CL} in linear scale). The 20 log rule is used to convert a linear voltage gain into a decibel voltage gain: $G = 20 \times \log A$.

$$V_{out} / V_{in} = A_{CL} = A_V / (1 + A_V \times B)$$
$$= 1 / \{B (1 + 1 / A_V \times B)\}$$

where A_V is the open-loop gain of an amplifier and B is the feedback factor. ($A_V \times B$) is called the loop gain. The denominator, ($1 + A_V \times B$), is called the amount of feedback. In the case of negative feedback, $A_V \times B < 0$. An op-amp has a very high A_V. Hence, $| A_V \text{ x } B | >> 1$. Therefore, the amount of feedback is calculated as $(1 + A_V \times B) \approx A_V \times B$ (loop gain). Hence, the above equation can be simplified as follows:

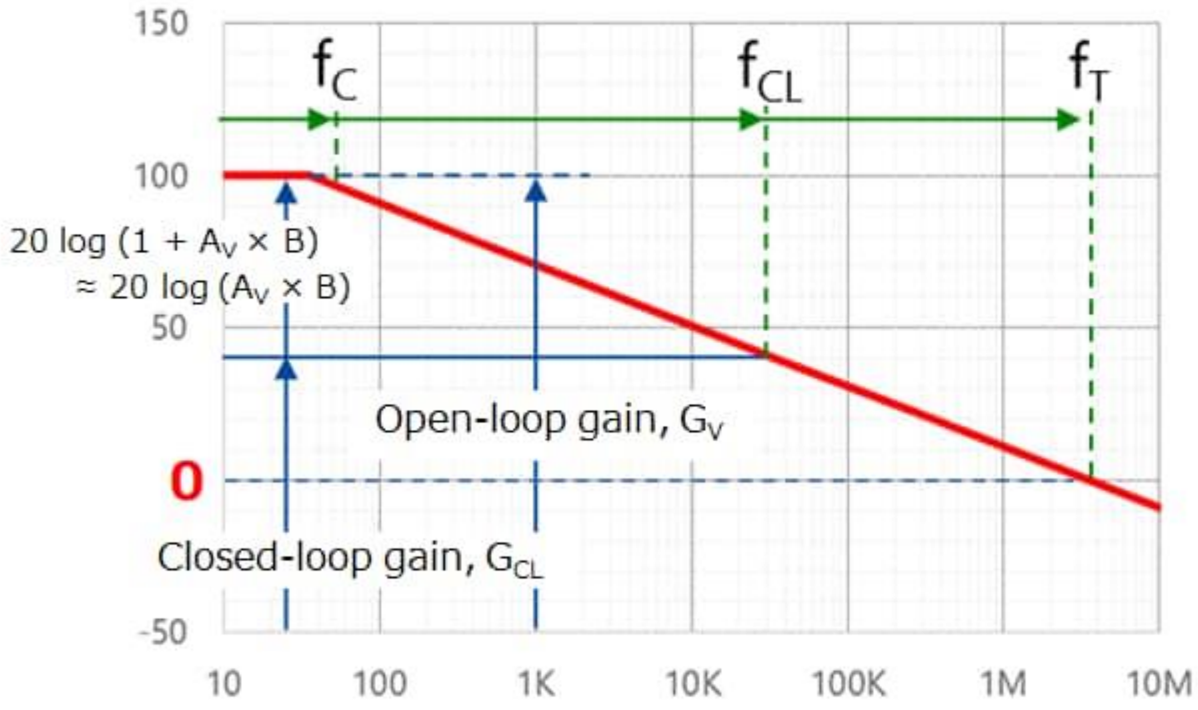
$$V_{out} / V_{in} = A_{CL} = 1/B$$

2. Open-loop and closed-loop gains (Increasing the bandwidth of an amplifier)

Figure shows this relationship. The op-amp has a bandwidth of f_C. With negative feedback, its closed-loop bandwidth expands to f_{CL}. f_{CL} is calculated as follows from the gain-bandwidth product equation:

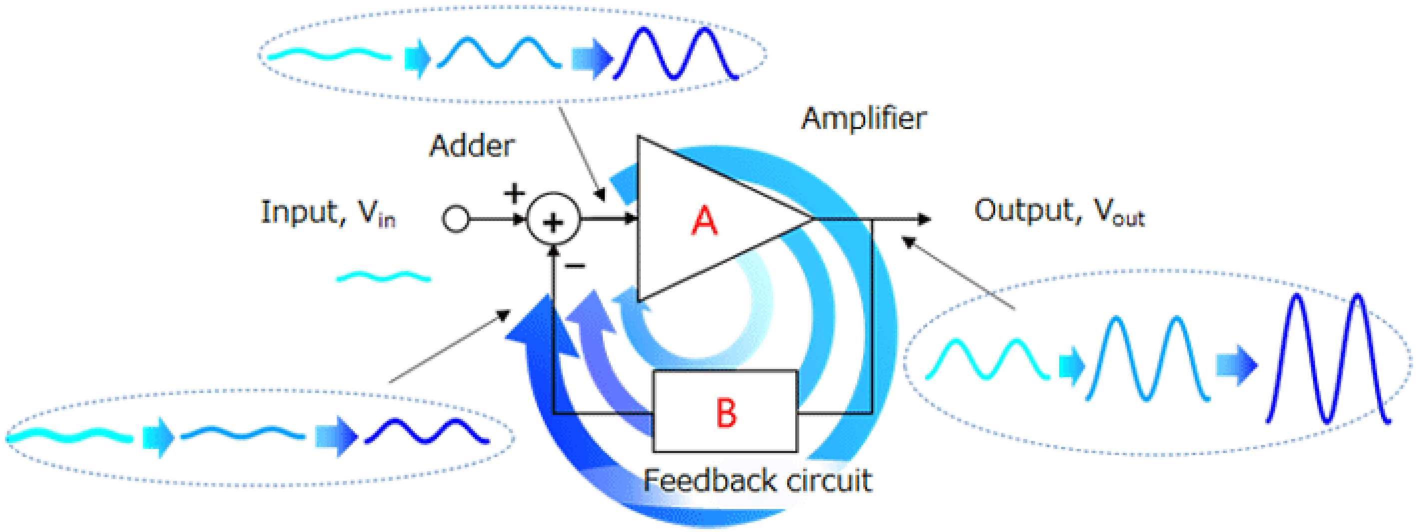
$$f_{CL} = f_T / A_{CL}$$

When the closed-loop gain (G_{CL}) or the bandwidth (f_{CL}) is insufficient, it is necessary to select an op-amp with high f_T.



3. Oscillation

An op-amp is normally used with a feedback circuit as shown in Figure. There are two types of feedback, positive and negative, as described in Section 1. When an op-amp is used as an amplifier, it is configured for negative feedback. Care is required as to the oscillation of a feedback circuit.
A signal or noise that acts as a source of oscillation can develop into oscillation under certain conditions. Here is a brief explanation about oscillation.
A source of oscillation applied to the input passes through the amplifier and the feedback circuit. Then, the adder adds it to the V_{in} input. Therefore, the output of the adder becomes larger than the initial state. As this process is repeated, the source of oscillation grows, causing oscillation. This is the characteristic of positive feedback.
You might think that oscillation is irrelevant as you use negative feedback. Even if it is negative feedback for the signal to be amplified, it might turn into positive feedback in the higher frequency band.

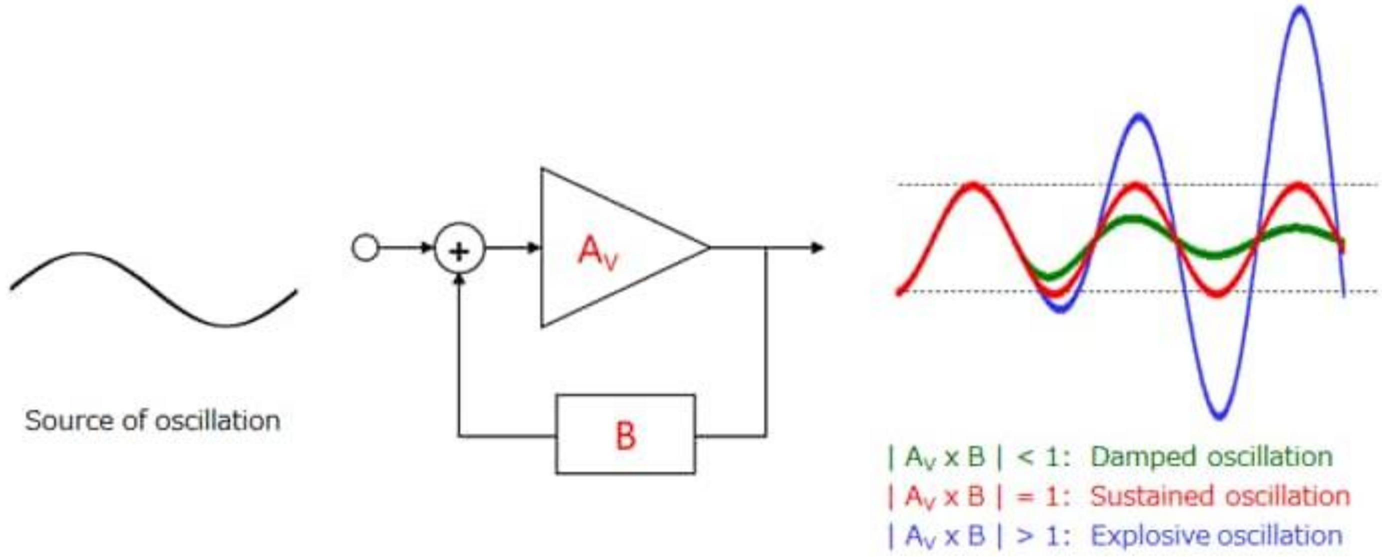


3. Oscillation

Let the open-loop gain of the op-amp be A_V and the feedback factor be B. Then, the transfer function of a feedback circuit is expressed as follows. Both A_V and B are complex numbers.

$$V_{out} = A_V / (1 + A_V \times B) \times V_{in}$$

In the case of a negative feedback circuit, $A_V \times B = +|A_V \times B|$. Therefore, V_{out} provides a stable output as described in Section 1. However, the phase of the output lags that of the input at high frequency since all circuits have a delay.
The feedback circuit turns into a positive feedback loop when this phase lag reaches 180 degrees.
The waveform of the output (V_{out}) differs as shown below, depending on the magnitude of the loop gain ($|A_V \times B|$) of positive feedback (i.e., when the signal from the feedback circuit has the same phase as the input signal). When a source of oscillation is applied to the input, a damped, sustained, or explosive oscillation occurs, depending on the magnitude of $|A_V \times B|$ at the frequency of the oscillation source. Generally, a sustained oscillation is called an oscillation. An explosive oscillation eventually subsides to a sustained oscillation since the open-loop gain (A_V) is restricted by the dynamic range of the amplifier.



3. Oscillation

A sustained oscillation occurs when the loop gain ($A_V \times B$) satisfies the following condition (i.e., the denominator of the transfer function becomes zero). This condition is called the Barkhausen condition for oscillation (or simply oscillation condition).

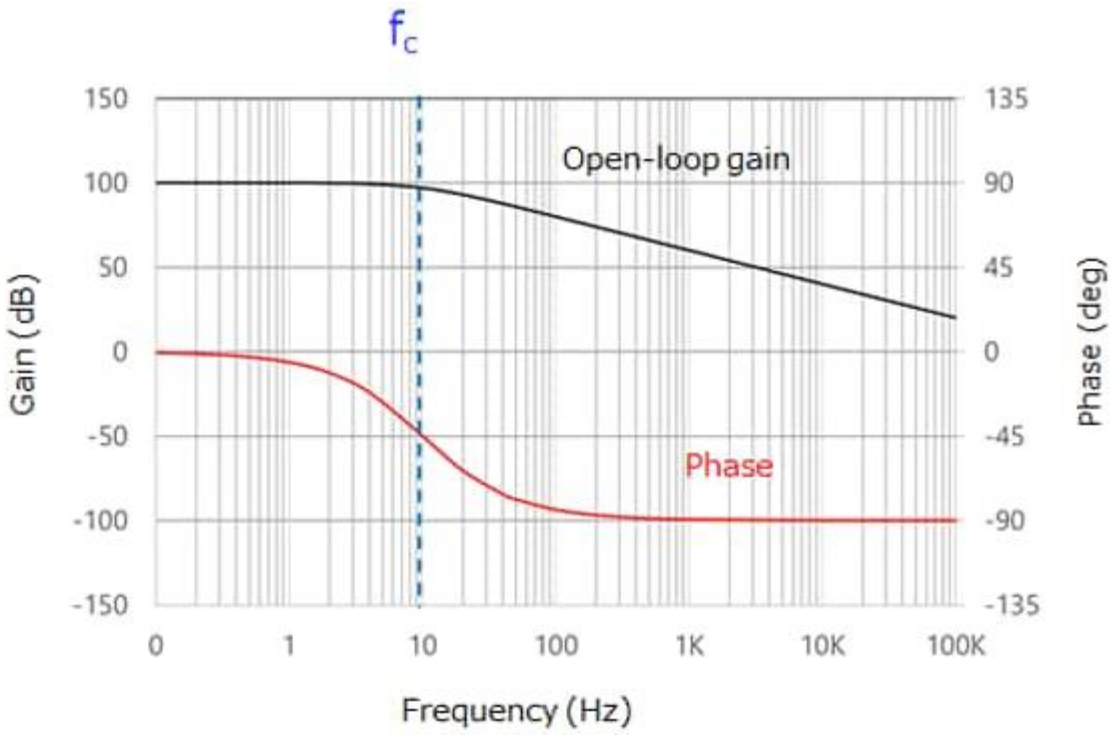
Amplitude condition: $R_e (A_V \times B) = -1$
Phase condition: $I_m (A_V \times B) = 0$

Note that an explosive oscillation eventually subsides to a sustained oscillation as described above. Therefore, the amplitude condition that causes abnormal oscillation is as follows:

Amplitude condition: $R_e (A_V \times B) < -1$

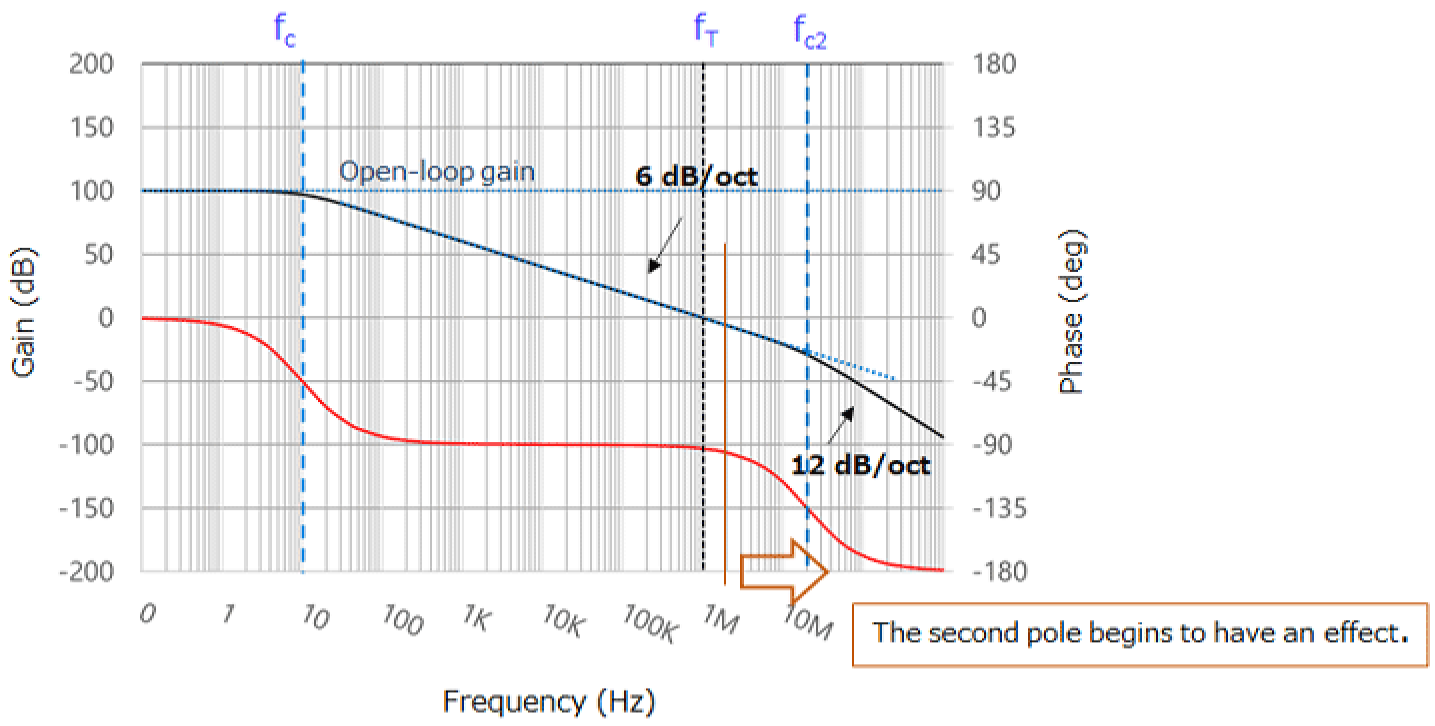
3. Oscillation

Because of an internal parasitic capacitance, an op-amp has a first-order delay element (as is the case with a first-order lowpass filter) as shown in Figure.
In the case of typical op-amps, the cut-off frequency of open-loop gain response is between 10 Hz and 100 Hz. The phase of the output lags 45 degrees behind in this frequency range. The phase lag is 90 degrees in the frequency range in which the open-loop gain decreases at a rate of 6 dB per octave.
If the gain-vs-frequency curve has such characteristics with only a main pole, a margin of 90 degrees remains until oscillation occurs. Therefore, oscillation is unlikely to occur.



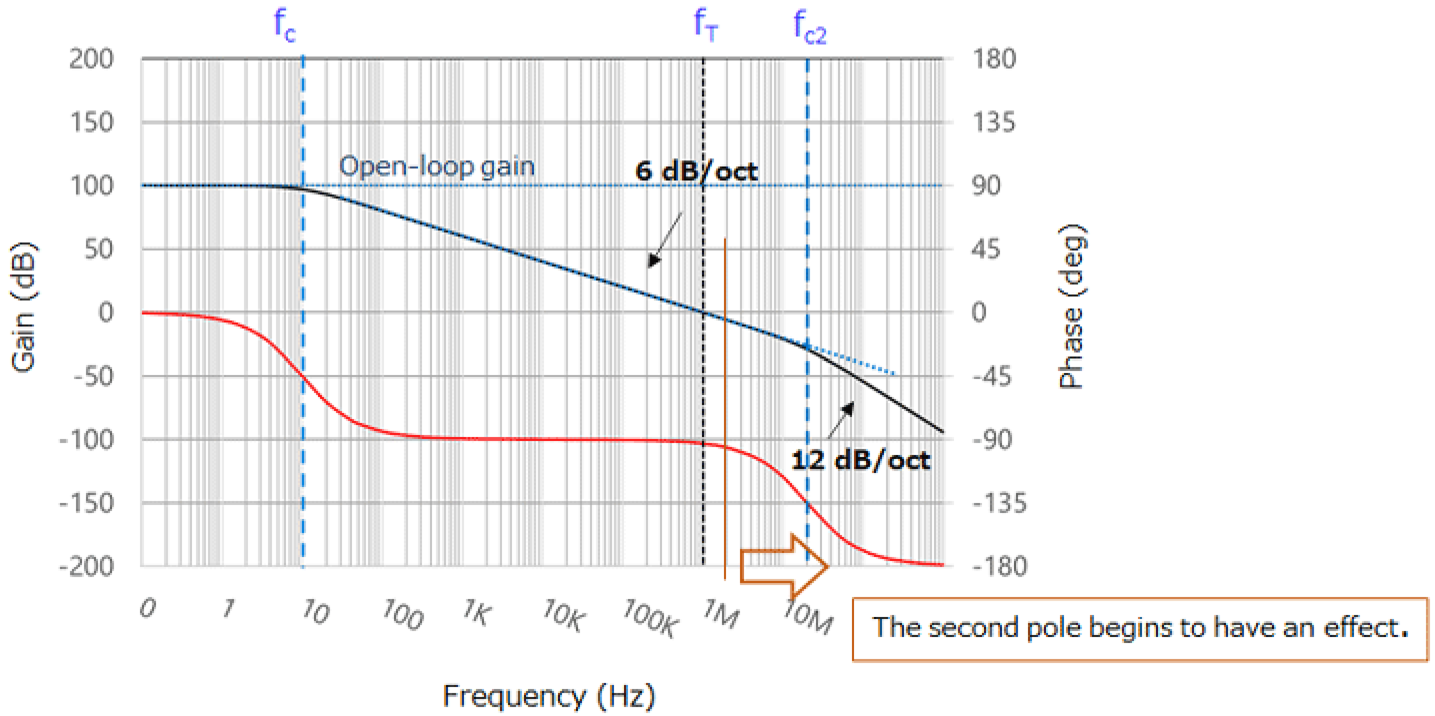
3. Oscillation

In reality, an op-amp has multiple poles. The cut-off frequency (f_c) shown in Figure is called the main pole. The frequency pole at f_{c2} close to the unity gain cross frequency (f_T) is called a second pole. Although there are more poles at higher frequencies, they do not cause any practical problem.



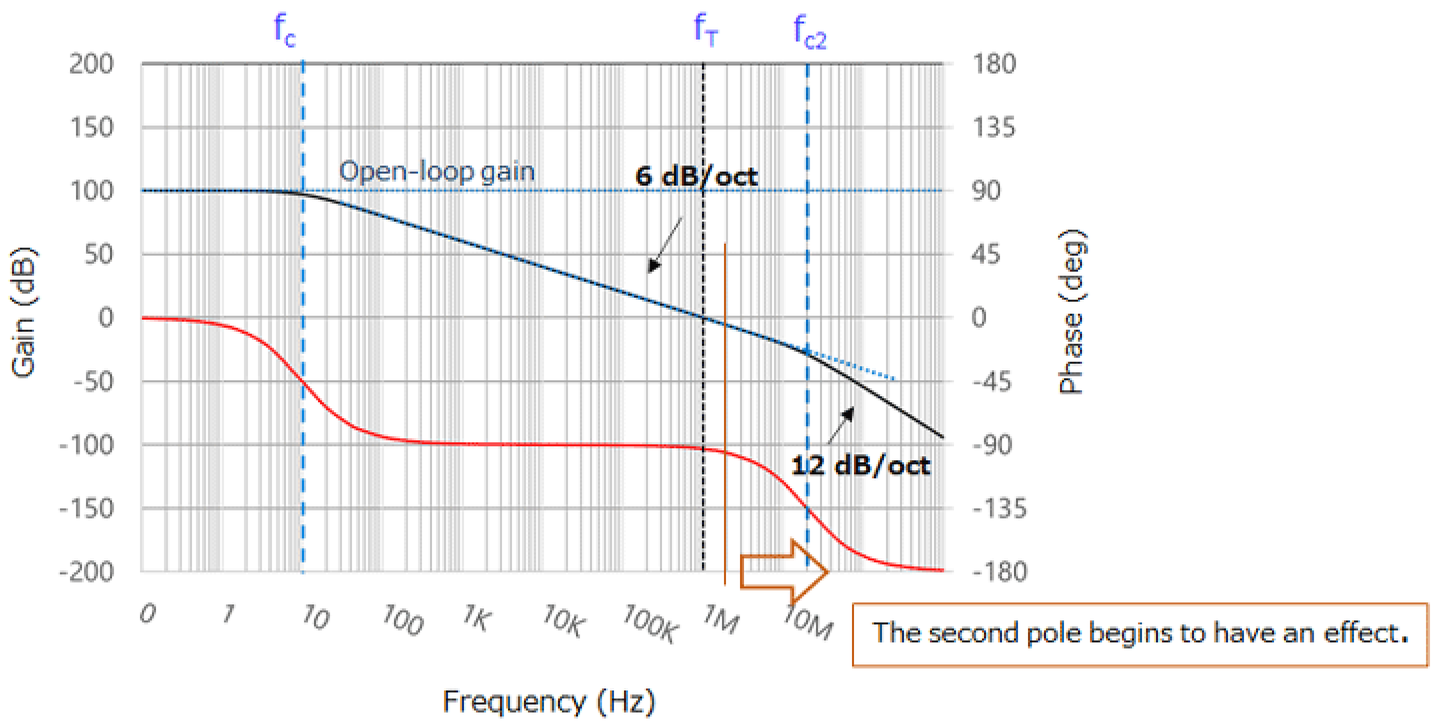
3. Oscillation

As shown in Figure, the slope of the open-loop gain curve changes from 6 dB per octave to 12 dB per octave at f_{c2}. The phase lag also increases further by another 45 degrees. This phase lag does not cause any problem when f_{c2} is higher than the unity gain cross frequency (f_T). However, even when f_{c2} is lower than f_T, care should be taken when using op-amps as unity gain amplifiers such as voltage followers. (If the datasheet for an op-amp states that it can be used with unity gain, it has a second pole at a frequency higher than f_T.)



3. Oscillation

In order to avoid abnormal oscillation, an op-amp should be used in the frequency range (f_c to f_{c2}) in which the open-loop gain decreases at a rate of 6 dB per octave. Note, however, that, at a frequency close to f_{c2}, an op-amp is affected by a second pole, causing a power loss and a phase delay. To avoid its effects completely, the closed-loop bandwidth (f_{CL}) should be less than one-fifth of f_{c2}.
Noise gain and loop gain are also related to oscillation.
For details, please refer to our application note “Basics of Operational Amplifiers and Comparators”.

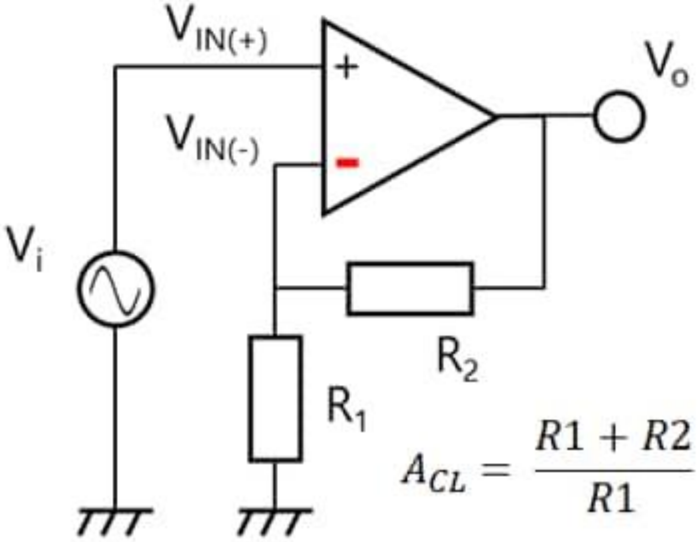


3. Oscillation

The above is a discussion on the oscillation of an op-amp itself.
It is also necessary to ensure that external circuitry is also free from oscillation (e.g., phase delay).
For example, this consideration applies to an application in which a capacitive load is driven by an op-amp. Oscillation occurs if the cut-off frequency due to the capacitive load is within the range in which the loop gain is greater than 1. In order to prevent oscillation, it is necessary, for example, to add a resistor in series with a capacitor. Even when an op-amp is not connected with a load, care should be taken as to wire or other capacitance. Minimize the length of the wire from the op-amp output to the subsequent device and that of the feedback loop.

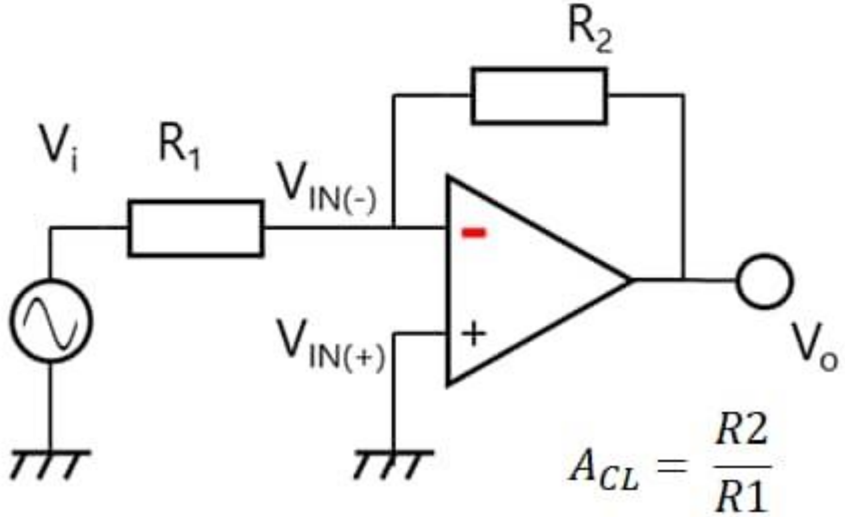
4. Basic op-amp applications

In the most basic form, op-amps are used as noninverting amplifiers and inverting amplifiers. Both noninverting and inverting amplifiers have negative feedback (with the output connected to $V_{IN(-)}$) as described in the previous section.
The closed-loop gain (A_{CL}) is shown in the following figures. The gain can be calculated easily by using the concept of a virtual short-circuit (also known as a virtual short, virtual ground or imaginary short) described in the next section.
The noninverting amplifiers have a very high input impedance since their input is directly connected to an op-amp. In contrast, the input impedance of the inverting amplifier is lower than that of the noninverting amplifier because $V_{IN(-)}$ and $V_{IN(+)}$ have the same potential as they are virtually short-circuited and because R_1 acts as input impedance.



$$A_{CL} = \frac{R1 + R2}{R1}$$

Noninverting amplifier

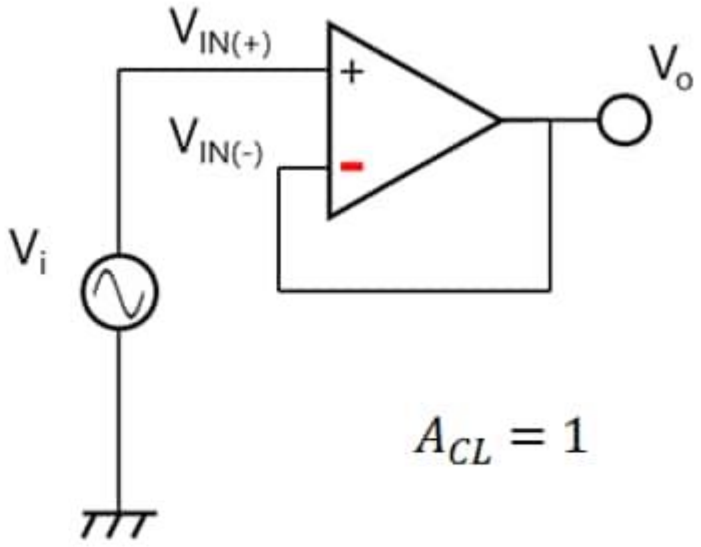


$$A_{CL} = \frac{R2}{R1}$$

Inverting amplifier

4. Basic op-amp applications

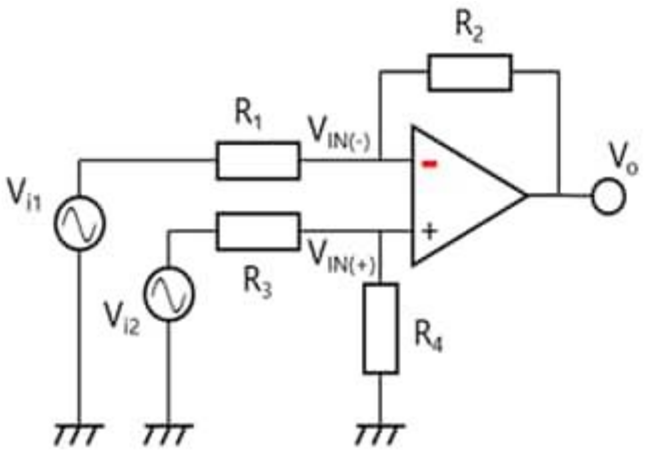
Figure shows a voltage follower. The voltage follower can be regarded as a noninverting amplifier with an R_1 of infinite resistance and an R_2 of zero. Since the voltage follower has a low gain (unity gain, A_V=1), it has a wide bandwidth. Therefore, care should be taken since it is susceptible to the effect of a second pole as discussed in Section 3, “Oscillation.” Most op-amps can be used as unity gain amplifiers since they have a second pole at a frequency sufficiently higher than the unity gain cross frequency (f_T). However, they might go into oscillation because of wire or load capacitance. If the datasheet for a given op-amp states that it can be used at a unity gain, it can be used as a voltage follower. Contact Toshiba’s sales representative if you want to use any other op-amp as a voltage follower.



Voltage follower

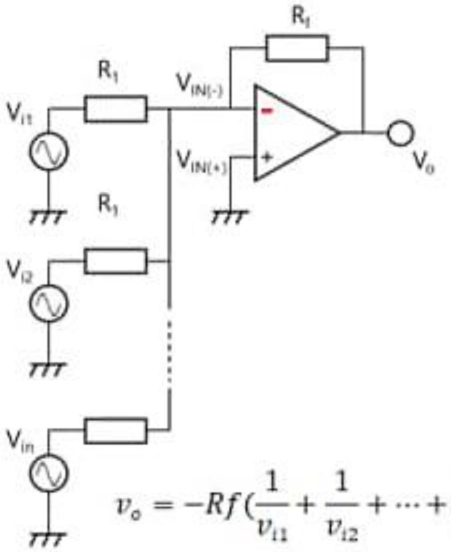
4. Basic op-amp applications

In addition, op-amps have various applications, including a differential amplifier (subtraction circuit) as well as an adder and integrator circuits.



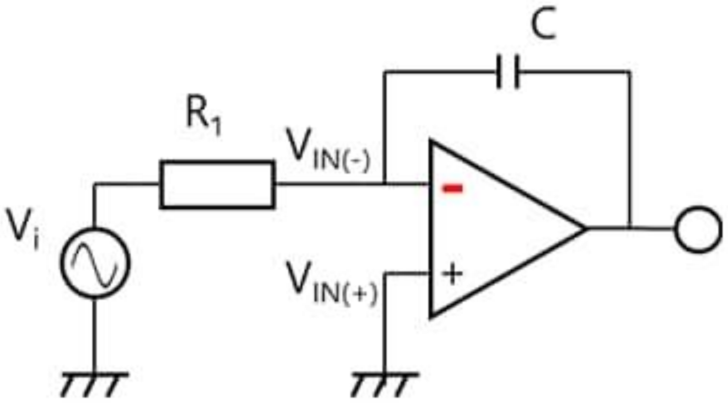
$$v_o = \frac{R_2}{R_1}(vi_2 - vi_1)$$

Differential amplifier (subtraction circuit)



$$v_o = -Rf\left(\frac{1}{v_{i1}} + \frac{1}{v_{i2}} + \cdots + \frac{1}{v_{in}}\right)$$

Addition circuit



$$v_o = -\frac{1}{C}\int \frac{v_i}{R_1}\,dt$$

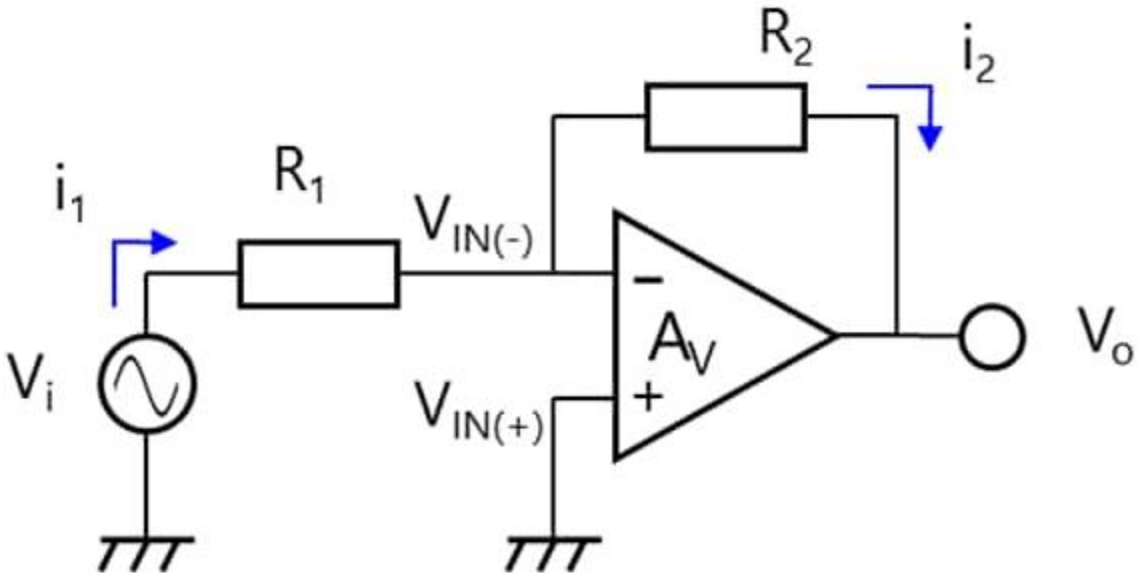
Integration circuit

5. Virtual short (virtual ground)

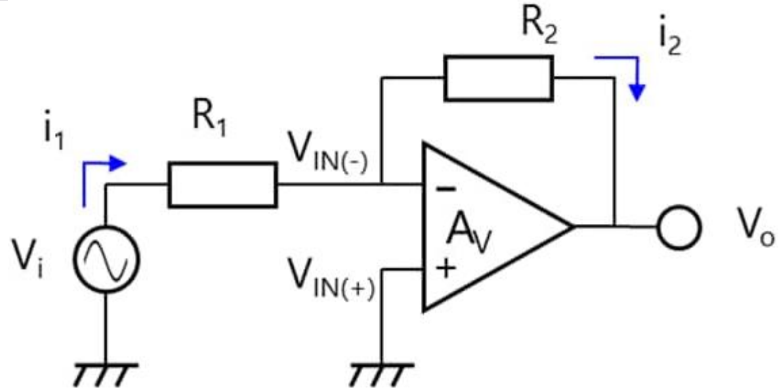
The closed-loop gain of an op-amp with negative feedback can be calculated easily using the concept of a virtual short-circuit (also known as a virtual short or virtual ground*).
The concept of a virtual short is that the $V_{IN\,(+)}$ and $V_{IN\,(-)}$ terminals of an op-amp with negative feedback have almost the same potential regardless of the input signal when it has a large open-loop gain.
Consider as follows to intuitively understand a virtual short.
An op-amp amplifies a difference in voltage between $V_{IN(+)}$ and $V_{IN(-)}$ by a factor of 100,000 or more (called the open-loop gain). However, a real op-amp has a finite output. Therefore, in a circuit without negative feedback, if the differential voltage is a sine wave of 1 Vpp, the output should be 100,000 Vpp, but generally the output is limited by the power supply voltage and ground. As a result, it becomes a saturated square wave at the voltage between the supply voltage and ground. Therefore, when a distortion-free output is obtained with an amplifier using an op-amp, the difference in voltage between the $V_{IN(+)}$ and $V_{IN(-)}$ inputs should be negligible.

5. Virtual short (virtual ground)

In the case of the negative-feedback amplifier (inverting amplifier) shown in Figure, the output is connected to the input in such a manner that an increase in output causes a decrease in input. As a result, the output signal fits between the power supply and ground. (Suppose, for example, that an inverting amplifier has an input voltage of 1 V_{pp} and a gain of 3 ($R_2 = 3 \times R_1$). Then, the output voltage becomes 3 V_{pp}.)
At this time, the op-amp is operating with an open-loop gain of 100,000. Since the output voltage is 3 V_{pp}, the input voltage is 3 V_{pp}/100,000 = 30 μV_{pp}. Hence, $V_{IN(-)} \approx V_{IN(+)}$.



5. Virtual short (virtual ground)



Next, let’s use simple calculations to understand this.
Figure shows a negative-feedback amplifier (inverting amplifier) using an op-amp.

Suppose that the op-amp is the ideal one. Then, the following are true:

1. Infinite open-loop gain (A_V)
2. Infinite input impedance
3. Zero output impedance

Since the input impedance is infinite, all of the current flowing through R_1 (i_1) flows through R_2.

$$i_1 = (V_i - V_{IN(-)}) / R_1 = (V_{IN(-)} - V_o) / R_2 \qquad (1)$$

The output voltage of the op-amp is given by the equation:

$$V_o = A_V \times (V_{IN(+)} - V_{IN(-)}) \quad (2)$$

From Equations 1 and 2, $V_{IN(+)}$ is calculated as follows:

$$V_{IN(+)} = \{1 + \underbrace{(R_1 + R_2) / (A_V * R_1)}_{\fallingdotseq 0}\} * V_{IN(-)} - \underbrace{R_2 * V_i / (A_V * R_1)}_{\fallingdotseq 0} \quad \cdots (3)$$

$$A_V \rightarrow \infty$$

Because the output impedance is zero, we obtain $V_{IN(+)} = V_{IN(-)}$ from Equation 3.
Hence, the voltage at the $V_{IN(-)}$ input is equal to that of the $V_{IN(+)}$ input connected to GND.
In this case, the condition of the $V_{IN(-)}$ input is called a virtual short.

5. Virtual short (virtual ground)

Next, let's calculate the closed-loop gain (A_V) of the noninverting amplifier shown in Figure using a virtual short and the ideal op-amp. Let's express the output voltage (V_o) as a function of V_i. From the concept of a virtual short, $V_{IN(-)} = V_{IN(+)} = V_i$. Therefore, the current flowing through R_1 (i_1) is calculated as follows:

$$I_1 = V_{IN(-)} / R_1 = V_i / R_1$$

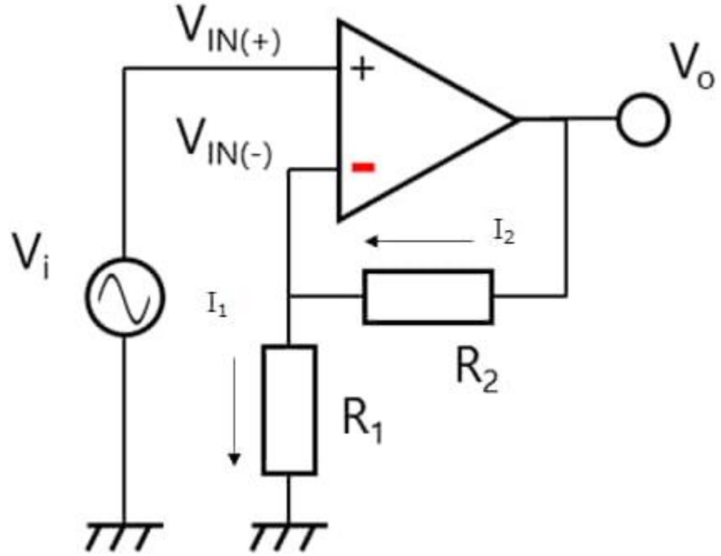
No current flows to the op-amp input since it has infinite impedance. Letting the current flowing through R_2 be I_2, $I_1 = I_2$. Hence, the voltage across R_2 (V_{R2}) is:

$$V_{R2} = R_2 \times I_2 = R_2 \times V_i / R_1$$

Hence, V_o is calculated as:

$$V_o = V_{R1} + V_{R2}$$
$$= V_i + R_2 \times V_i / R_1 = V_i \times (R_1 + R_2) / R_1$$
$$A_V = V_o / V_i = (R_1 + R_2) / R_1$$

You can easily find the closed-loop gain equation.



Noninverting amplifier

5. Virtual short (virtual ground)

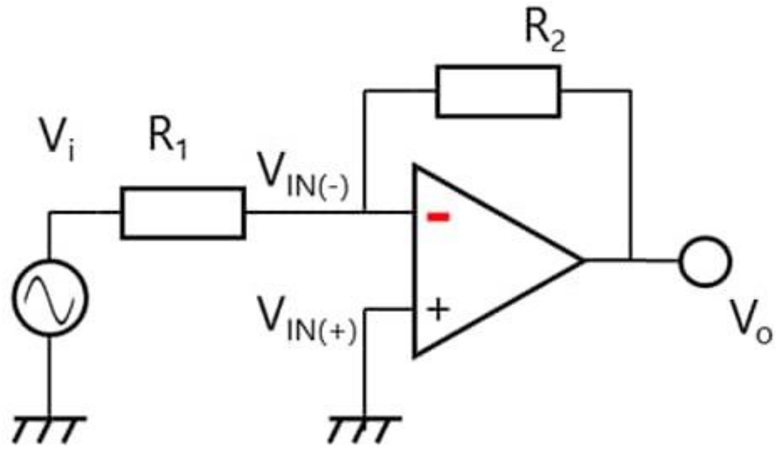
The closed-loop gain (A_V) of the inverting amplifier shown in Figure can also be calculated in the same manner.

$$V_{IN(-)} = V_{IN(+)} = 0\ \text{V (GND)}$$
$$I_1 = V_1 / R_1 = I_2$$
$$V_o = V_{R2} = R_2 \times I_2 = R_2 \times V_1 / R_1$$

Hence, the closed-loop gain is:

$$A_V = V_o / V_i = R_2 / R_1$$

As described above, the closed-loop gain can be calculated easily using the concepts of a virtual short and the ideal op-amp.



Inverting amplifier

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