An amplifier is defined as the ratio of the output and input voltage amplitudes:

\[
\frac{V_o}{V_i} = A
\]

Consequently, we model the amplifier as a two-port device with an input and output port. The voltage amplification factor, or gain, is a measure of how much the amplifier boosts an input signal. The output signal is proportional to the input signal.

**Chapter 5: Analog Signal Processing Using Operational Amplifiers**

**Introduction**

1. **Operational Amplifiers**
   - Understanding the characteristics and limitations of a "real" operational amplifier
   - Design an inverse amplifier: Monolithic amplifier, inverting, non-inverting, feedback amplifier
   - Understand the important characteristics of an operational amplifier

**Objectives:** After you read, discuss, study, and apply ideas in this chapter, you will be able to:

- Have a clear understanding of the transducer and instrumentation design
- Comprehend the inverse information usually due to poor transducer design or-in

- **Signal Amplification**
- **Operational Amplifiers**

Be careful; usually due to an electronic interface.
We will consider most of these applications in subsequent sections. The design and operation of differential amplifiers is based on the following assumptions:

1. The signal is a steady-state condition.
2. The power supply is constant and stable.
3. The input signal is small compared to the power supply.
4. The output signal is also small compared to the power supply.

These assumptions allow for the use of simplified models for the amplifier circuit. For example, the ideal op-amp model shown in the figure assumes no errors or limitations, which is not true in practice. However, these models provide a good starting point for understanding amplifier behavior.

For the operational amplifier described in the next section, let's consider the following equations:

\[ V_{out} = A \cdot V_{in} \]

where \( A \) is the gain of the amplifier.

\[ Z_{out} = \frac{1}{A} \cdot Z_{in} \]

where \( Z_{out} \) is the output impedance of the amplifier.

These equations are used to calculate the output voltage and impedance of the amplifier, respectively. The gain of the amplifier is determined by the ratio of the output voltage to the input voltage.

Figure 5.4 shows the ideal op-amp model and its schematic representation. The model includes an inverting input and a non-inverting input, which are connected to the amplifier's inputs. The output of the amplifier is connected to the load resistor, which provides a feedback path to the input circuit.

The operational amplifier, or op-amp, is a low-cost and versatile integrated circuit that can be used in a wide variety of applications. It is designed to amplify small signals, process signals, and perform various signal processing tasks. The op-amp is a key component in many electronic systems, including audio amplifiers, video amplifiers, and control systems.
CHAPTER 5: Analog Signal Processing Using Operational Amplifiers

FIGURE 5.4 441 operational amplifier.

FIGURE 5.5 441 op-amp pinout.

FIGURE 5.6 441 internal design (Courtesy of National Semiconductor, Santa Clara, CA).

FIGURE 5.7 441 pinout diagram.
Figure 5.8 illustrates the operation of an inverting amplifier and shows the voltage gain of the amplifier, which is determined simply by the expression:

\[ V_{out} = \frac{V_{in}}{A} \]

This equation is derived from Equation 5.10 by substitution into Equation 5.8.

Applying Kirchhoff's Voltage Law at node C and using the assumption that no current enters or leaves the ideal model shown in Figure 5.7, we can write:

\[ V_{in} = A \cdot V_{out} \]

where \( V_{in} \) and \( V_{out} \) are the input and output voltages, respectively.

In an inverting amplifier, the feedback is controlled by connecting two external resistors to do this.
The circuit is shown in FIGURE 5.10. The circuit is a noninverting amplifier. Therefore, the noninverting amplifier has a positive gain greater than one.

\[ \frac{Y_{out}}{Y_{in}} = 1 + \frac{R_2}{R_1} \]

Using Equations 5.14 and 5.16, the voltage gain can be written as

\[ Y_{gain} = \frac{R_2}{R_1} \]

so Equation 5.12 can be written as

\[ Y_{gain} = \frac{R_2}{R_1} \]

Applying KCL at node C gives

\[ \frac{R_2}{R_1} + \frac{R_{non}}{R_{non}} = \frac{R_{non}}{R_{non}} \]

Solving Equation 5.13 gives

\[ \frac{R_2}{R_1} = \frac{1}{1+R_{non}/R_{non}} \]

and applying the law of voltage differences gives

\[ \frac{R_2}{R_1} = \frac{1}{1+R_{non}/R_{non}} \]

The equation for the noninverting amplifier is:

\[ \frac{V_{out}}{V_{in}} = 1 + \frac{R_2}{R_1} \]

The schematic of a noninverting amplifier is shown in FIGURE 5.11.
Difference Amplifier Circuit

\[ \frac{V_{in}}{V_{out}} = \frac{R}{R} \]

(5.21)

Since \( V_{in} \) is divided between resistors \( R \) and \( R' \)

\[ \frac{V_{in}}{V_{out}} = \frac{R}{R'} \]

(5.22)

Equation 5.11 is used to derive \( \frac{V_{in}}{V_{out}} \):

S'7

The output of the circuit shown in Figure 5.16 where the input voltage is

\[ \frac{V_{in}}{V_{out}} = \frac{R}{R'} \]

5.19

we can show (see Question 5.1) that

\[ \frac{V_{in}}{V_{out}} = \frac{R}{R'} \]

5.18

amplifying the circuit with

The sum of the circuits shown in Figure 5.13 is used to add and subtract signals. By

SUMMER

S'7

In physics, speakers are devices that produce sound. When we want to produce sound, we use the speakers to convert electrical signals into mechanical vibrations. The speakers vibrate and produce sound waves that travel through the air and reach our ears. The sound we hear is a result of these vibrations. The speakers are driven by electronic circuits that convert the electrical signals into mechanical vibrations. These circuits use transistors, diodes, and other electronic components to amplify and filter the signals. The amplified signals are then fed to the speaker's terminals, where they cause the speaker's diaphragm to vibrate and produce sound. The sound produced by the speaker is a direct result of the electrical signals fed to it.
- Consistent bandwidth over a large range of gains.
- Mean in differential output square signal conditioning applications.
- Capability to amplify low-level signals in noisy environments, often a requirement.
- Mode gain to suppress high-frequency noise that are common to both inputs.
- When the inputs are equal and nonzero, it is desirable to minimize the common
  mode gain. The common mode gain is minimized if the amplifier will be configured
  to cancel the common mode input. The common mode gain is determined by
  applying an infinite input resistance to the output of the amplifier. For a
  given amplifier, the common mode gain is the differential mode gain divided
  by the common mode gain. The common mode gain is the ratio of the
  differential mode gain to the common mode gain. The common mode gain is
  the ratio of the differential mode gain to the common mode gain.

**Instrumentation Amplifier**

(5.23) \[
V_{in} - V_{out} = A V_{in}
\]

This result can also be obtained using the op amp rules, KCL, and Ohm's Law (see

\[
\frac{V_{in} - V_{out}}{\frac{R}{2}} = \frac{m_o V_{in}}{2}
\]

When \( R' = R = 2R \), the output voltage is an amplified difference of the input volt.

(5.24) \[
A \left( \frac{V_R}{R} + \frac{V_O}{2R} \right) = \frac{m_o V_{in}}{2} + \frac{m_o V_{out}}{2} = \frac{m_o V_{in}}{2}
\]

The principle of superposition implies that the total output \( V_{out} \) is the sum of

\[
A \left( \frac{V_R}{R} + \frac{V_O}{2R} \right) = \frac{m_o V_{in}}{2}
\]

By substituting Equation 5.21, this equation can be written as

\[
A \left( \frac{V_R}{R} + 1 \right) = \frac{m_o V_{in}}{2}
\]

Therefore, the output is proportional to the input \( V_{in} \), as given by Equation 5.17

The circuit in Figure 5.16 is a non-inverting amplifier (see Figure 5.10).

**Figure 5.16**

Different amplifier with \( V_{in} \) shown.

**Figure 5.15**

Different amplifier with \( V_{in} \) shown.
and current for a capacitor. In the relationship between voltage and current, a resistor is replaced by a capacitor, and an input amplifier is replaced by a resistor. Figure 7.17 shows the strategy for the analysis. If the feedback resistor of the input amplifier is replaced by a capacitor, the result is

**figure 7.17**

1. 

\[ \frac{1}{2} \int \frac{1}{I} + 1 = \frac{1}{I} \alpha \Lambda \]

Integration gives

\[ \frac{1}{I} \alpha \Lambda = \frac{1}{P} \alpha \Lambda \]

2. (3.21)

For a capacitor, the voltage across a capacitor is given by

\[ V = \frac{1}{C} \int I \, dt \]

3. (3.22)

Applying Ohm’s Law to the circuit gives

\[ I = \frac{V}{R} \]

4. (3.23)

Applying Ohm’s Law to the circuit gives

\[ I = \frac{V}{R} \]

5. (3.24)

Applying Ohm’s Law to the circuit gives

\[ I = \frac{V}{R} \]

### Chapter 5: Analog Signal Processing and Operational Amplifiers

Introduction to Microelectronics and Measurement Systems
\[
\frac{IP}{\omega AP} \cdot \omega F = \omega^0 A
\]

Since \( i_F = i_m \cdot \omega^0 \) and \( v_m = v_{in} \cdot \omega^0 \),

\[
\omega \frac{C}{\omega F} = \frac{IP}{\omega AP}
\]

and current for a capacitor. Equation 5.5 is replaced by the relationship between voltage and current in Eq. 5.3. \(^{24}\) Referring to the analysis for the differentiator circuit, it is shown in Fig. 5.2. Referring to the analysis for the inverting amplifier, Equation 5.5 is replaced by the relationship between voltage and current:

**DIFFERENTIATOR**

If the input resistance of the inverting op amp is replaced by a capacitor, the result is a differentiator. The relationship between voltage and current is:

\[
\frac{v_F + v_m}{i_F} = \omega^0 C
\]

Equation 5.6

The reason for this is that the input bias current flowing into the inverting terminal flows into the capacitor and the noninverting terminal receives no current. If the input resistance is high, \( r_m \) and the input bias current flowing into the noninverting terminal flows through \( r_m \) and the input bias current flowing into the inverting terminal is not affected by the input bias current. Therefore, the output signal is a scaled integral of the input signal.

\[
1P(\omega) \int_0^t \frac{v_F}{\omega} dt = (1)^0 A
\]

where \( V_F(v) \) is the output voltage generated by the input voltage, \( v_{in} \). Thus, the output voltage is a scaled integral of the input voltage. This is illustrated in Fig. 5.6. Therefore, the output signal is a scaled integral of the input signal:

**IMPROVED INTEGRATOR**

**FIGURE 5.19**

**IDEAL INTEGRATOR**

**FIGURE 5.18**

CHAPTER 5: ANALOG SIGNAL PROCESSING USING OPERATIONAL AMPLIFIERS

INTRODUCTION TO MECHATRONICS AND MEASUREMENT SYSTEMS
Sample and Hold Circuit

The sample-and-hold circuit is used extensively in analog-to-digital conversion.

Sample and hold circuit

Figure 5.20

The sample and hold circuit is used extensively in analog-to-digital conversion.

Sample and hold circuit

Figure 5.20

The sample and hold circuit is used extensively in analog-to-digital conversion.

Sample and hold circuit

Figure 5.20

The sample and hold circuit is used extensively in analog-to-digital conversion.
can be used without signal attenuation or distortion. It is an especially useful amplifier for medium-frequency applications, and is often referred to as a "medium-frequency" amplifier. A medium-frequency amplifier is capable of handling signals in the range of 500 Hz to 5 MHz.

The output of a medium-frequency amplifier is typically a voltage signal, which is proportional to the input signal. The gain of a medium-frequency amplifier is usually measured in decibels (dB), which is a logarithmic scale commonly used to express signal levels.

A medium-frequency amplifier is often used in applications where the input signal is a low-level signal, such as in audio systems or in instrumentation. In such applications, the amplifier must be able to handle a wide range of signals, from very low levels to very high levels, without distorting the signal.

Another important characteristic of a medium-frequency amplifier is its bandwidth. The bandwidth of a medium-frequency amplifier is the range of frequencies over which the amplifier can operate without significant distortion. A medium-frequency amplifier typically has a bandwidth of 10,000 Hz to 5 MHz.

In order to quantify the step response of a medium-frequency amplifier, a step input is applied to the amplifier input, and the output is measured. The step response of a medium-frequency amplifier is typically a smooth, undistorted signal, without any significant ringing or overshoot.

**Figure 5.32**
Effect of slewing rate on a square wave.

**Figure 5.33**
Comparison of slewing rate.
These graphs are also provided on the data sheet.

These graphs show the transfer functions characteristics of the LT073. The data sheet is typical of those from other manufacturers. It is divided into a maximum section and an equivalent operational amplifier section. If it is divided into a maximum gain section and an equivalent operational amplifier section, it is not a reproduction of the LT073 data sheet.

Data for each of the parameters above are usually provided in a manufacturer's data sheet.

It is important to ignore the section that produces a gain of 1. The gain is the gain of the operational amplifier with the input open and the output shorted.

The graph shows the gain (dB) of the operational amplifier as a function of frequency. The gain is defined as the ratio of the output voltage to the input voltage.

The amplifier gain is measured at a specific frequency, which is usually 1 kHz. The gain of the amplifier is then plotted against the frequency on a log-log scale.

The graph shows the frequency response of the operational amplifier. The gain is plotted on a log-log scale, and the frequency is plotted on a linear scale.

The operational amplifier gain is measured at a specific frequency, which is usually 1 kHz. The gain of the amplifier is then plotted against the frequency on a log-log scale.

The amplifier gain is defined as the ratio of the output voltage to the input voltage.

The amplifier gain is measured at a specific frequency, which is usually 1 kHz. The gain of the amplifier is then plotted against the frequency on a log-log scale.

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The amplifier gain is defined as the ratio of the output voltage to the input voltage.

The amplifier gain is measured at a specific frequency, which is usually 1 kHz. The gain of the amplifier is then plotted against the frequency on a log-log scale.
### Chapter 5: Analog Signal Processing Using Operational Amplifiers

#### Absolute Maximum Ratings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Temperature Range</td>
<td>-25°C to 70°C</td>
</tr>
<tr>
<td>Storage Temperature Range</td>
<td>-40°C to 85°C</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>25% to 85% non-condensing</td>
</tr>
</tbody>
</table>

#### Electrical Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Voltage</td>
<td>5 V, 12 V, 15 V</td>
</tr>
<tr>
<td>Gain Bandwidth Product</td>
<td>0.1 MHz</td>
</tr>
<tr>
<td>Power Dissipation</td>
<td>0.5 W</td>
</tr>
</tbody>
</table>

#### Example of I/O Data Sheet

| (continued) |

**Figure 5.25**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Voltage</td>
<td>5 V, 12 V, 15 V</td>
</tr>
<tr>
<td>Power Dissipation</td>
<td>0.5 W</td>
</tr>
</tbody>
</table>

#### Table 5.1: Gain Bandwidth Product

<table>
<thead>
<tr>
<th>Supply Voltage</th>
<th>5 V</th>
<th>12 V</th>
<th>15 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain Bandwidth Product</td>
<td>0.1 MHz</td>
<td>0.1 MHz</td>
<td>0.1 MHz</td>
</tr>
</tbody>
</table>

#### Table 5.2: Power Dissipation

<table>
<thead>
<tr>
<th>Supply Voltage</th>
<th>5 V</th>
<th>12 V</th>
<th>15 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Dissipation</td>
<td>0.5 W</td>
<td>0.5 W</td>
<td>0.5 W</td>
</tr>
</tbody>
</table>

---

**Note:** For more detailed specifications and performance data, consult the manufacturer's data sheet for the specific operational amplifier being used.
DESIGN EXAMPLE 5.1: Magnetic Control of a Prosthetic Limb

Here is the output current: 5 mA, which is well within the op amp's capabilities. The design focuses on minimizing the power dissipation. The circuit is shown in the following diagram.

**Example 5.1:** Setting Resistors for Op Amp Circuits. The ideal model.

**Figure 5.26**

![Diagram of magnetic control of a prosthetic limb](attachment://image.png)

**Chapter 5: Analog Signal Processing Using Operational Amplifiers**

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Look like the following:

At this point the EKG signal presented by the oscilloscope would

The information amplifier was chosen because it can extract a much clearer EKG signal than other methods. When the noise is filtered out, the signal becomes clearer, and it is easier to see the actual heartbeat.

The information amplifier is crucial in amplifying the EKG signal, especially when the noise is significant. By amplifying the signal, it becomes easier to observe the heartbeat and other electrical activities in the heart muscle.
In summary, we have used a variety of operational amplifiers and circuits to process an input signal. The low-pass filtered signal is basically the envelope of the original EMG signal. However, to recover the signal, we need to use a precision rectifier (see figure below). This circuit converts the EMG signal into a binary control signal for the motor controller. The resulting low-pass filtered signal can then be used to control the motor.

The circuit diagram shows the low-pass filter used to remove high-frequency components from the signal. The filter consists of resistors and capacitors connected in a specific way to ensure that only the low-frequency components pass through.

The precision rectifier is used to convert the binary control signal into a DC voltage, which can be used to control the motor.
5.5 Determine $V_o$ as a function of $I$ for each of the op amp circuits shown below. Assume ideal op amp behavior.

5.4 Derive Equation 5.31, that expresses $V_{out}$ in terms of $V_{in}$ and $A_o$, shown in Figure 5.3.

5.3 Derive Equation 5.24 for the difference amplifier without using the principle of superposition.

5.2 Analyze the circuit in Figure 5.13, and determine an equation for the output voltage. Show and explain all work.

5.1 Using the input waveform below, sketch the corresponding output waveform for each op amp circuit. Assume ideal op amp behavior.

CHAPTER 5: Analog Signal Processing Using Operational Amplifiers

Questions and Exercises

Introduction to Mechatronics and Measurement Systems
5.10. Use the principle of superposition to derive an expression for the output voltage in the circuit on the next page and explain why the circuit is called a level shifter.

5.8. Find \( \Delta V \) as a function of \( \theta \) in the op amp circuit below.

5.9. Explain why \( \Delta V \neq 0 \) in the circuit below.

5.6. Determine \( V_{out} \) in the circuit below with \( R_1 = 1 \text{ k\Omega}, R_2 = 5 \text{ k\Omega}, V = 1 \text{ V}, \) and \( \Delta V = 5 \text{ V}. \)

5.7. Determine \( I \) in terms of \( \Delta V \), \( R_1 \), \( R_2 \), and \( I \) in the circuit below. Assume ideal op amp behavior.

CHAPTER 5: ANALOG SIGNAL PROCESSING USING OPERATIONAL AMPLIFIERS
Solve the circuit and graph open loop gain curve below. What is the approximate bandwidth for the circuit when $R_L = 20\,\text{k}\Omega$ and $R = 2\,\text{k}\Omega$?