POLYTECHNIC 2nd SEMESTER

Fundamentals of Electrical & Electronics Engineering

CHAPTER NOTES

OVERVIEW OF
ANALOG CIRCUITS

Operational Amplifiers (OPAMP)

1. Features of an Ideal OPAMP, Pin Configuration of 741C, Virtual Ground & Offset Null
2. Inverting and Non-Inverting Mode — Working and Gain Calculation
3. Applications of OPAMP: Amplifier, Adder, Integrator & Differentiator

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1. Ideal OPAMP Features, 741C Pin Config, Virtual Ground & Offset Null

1.1 What is an Operational Amplifier (OPAMP)?

An Operational Amplifier (OPAMP) is a high-gain, direct-coupled differential amplifier that amplifies the voltage difference between its two input terminals. Originally designed to perform mathematical operations such as addition, subtraction, integration, and differentiation in analog computers, the OPAMP has evolved into the most versatile and widely used linear integrated circuit in electronics.

The most popular and historically significant OPAMP is the μA741 (commonly called the 741C), introduced by Fairchild Semiconductor in 1968. It is available as an 8-pin Dual Inline Package (DIP) and is still widely used in laboratories, educational settings, and practical circuits. It operates on dual power supply (typically ±15 V) and can drive output voltages up to approximately ±13 V.

Symbol: The OPAMP is represented by a triangle pointing toward the output. It has two input terminals — the Inverting Input (−) and the Non-Inverting Input (+) — and one output terminal.

1.2 Features of an Ideal OPAMP

An ideal OPAMP is a theoretical model used to simplify circuit analysis. Although real OPAMPs (like the 741C) do not perfectly match these ideal characteristics, they approximate them closely enough for most practical purposes. The key features of an ideal OPAMP are:

Ideal OPAMP Parameter	Ideal Value	Practical 741C (Approx.)
Open-Loop Voltage Gain (AOL)	Infinite (∞)	~200,000 (106 dB)
Input Impedance (Zin)	Infinite (∞)	~2 MΩ
Output Impedance (Zout)	Zero (0 Ω)	~75 Ω
Bandwidth (BW)	Infinite (∞)	~1 MHz (unity gain)
Common Mode Rejection Ratio (CMRR)	Infinite (∞)	~90 dB
Input Offset Voltage	Zero (0 V)	~1–6 mV
Input Bias Current	Zero (0 A)	~80 nA
Slew Rate	Infinite (∞)	~0.5 V/μs
Noise	Zero	Present (low)
Temperature Drift	Zero	Small but present

Explanation of Key Ideal Parameters

- **Infinite Open-Loop Gain:** Infinite Open-Loop Gain (AOL = ∞)

- The ratio of output voltage to the differential input voltage without any feedback. In practice this is around 100,000 to 200,000. This high gain allows the OPAMP to produce a large output even for a tiny input difference.
- **Infinite Input Impedance:** Infinite Input Impedance (Zin = ∞)
- No current flows into either input terminal — the OPAMP draws no current from the source circuit. This ensures that the OPAMP does not load the preceding stage.
- **Zero Output Impedance:** Zero Output Impedance (Zout = 0)
- The output of an ideal OPAMP behaves as a perfect voltage source — it can supply any amount of current to the load without the output voltage drooping.
- **Infinite Bandwidth:** Infinite Bandwidth
- An ideal OPAMP amplifies all frequencies equally, from DC to infinite frequency. In practice, the gain drops at higher frequencies and the 741C has a gain-bandwidth product of about 1 MHz.
- **Infinite CMRR:** Infinite CMRR
- The OPAMP completely rejects common-mode signals (signals present equally at both inputs) and amplifies only the differential signal. A high CMRR is critical for noise rejection in measurement circuits.

1.3 Pin Configuration of the µA741C

The µA741C is packaged in an 8-pin Dual Inline Package (DIP). Understanding the function of each pin is essential for correctly designing OPAMP circuits. The pin diagram is described below:

Pin 2 → Inverting Input (−)	┌────────────┐	
Pin 3 → Non-Inverting Input (+)	│ µA741C ├─→ Pin 6 Output	
	│ OPAMP IC │	
Pin 7 → +VCC (Positive Supply)	│ (Dual Supply ±15V) │	
Pin 4 → −VEE (Negative Supply)	└────────────┘	
Pins 1 & 5 → Offset Null	**Pin 8 → NC (No Connection)**	

Pin	Name / Function	Description
1	**Offset Null (−)**	Used with a potentiometer to null the output offset voltage
2	**Inverting Input (V−)**	The inverting (−) input terminal of the differential amplifier
3	**Non-Inverting Input (V+)**	The non-inverting (+) input terminal of the differential amplifier
4	**V− (Negative Supply)**	Negative power supply terminal (typically −15 V)
5	**Offset Null (+)**	Second terminal of the offset null potentiometer
6	**Output**	The amplified output signal terminal
7	**V+ (Positive Supply)**	Positive power supply terminal (typically +15 V)

8	**NC (No Connection)**	Not internally connected — present for standard 8-pin DIP package symmetry

Power Supply: The 741C requires a dual (bipolar) power supply: +VCC (Pin 7) and −VEE (Pin 4). Standard values are ±15 V, though it can operate from ±5 V to ±18 V. Both supply rails are referenced to a common ground.

1.4 Concept of Virtual Ground

Virtual Ground is one of the most important and frequently used concepts in OPAMP circuit analysis. It arises from the ideal OPAMP assumption of infinite open-loop gain combined with negative feedback. In an inverting amplifier configuration, the non-inverting input (Pin 3) is connected directly to the actual ground (0 V). Due to the infinitely high open-loop gain, even a microscopic voltage difference between the two input terminals would produce a huge output. In practice, with negative feedback applied, the output adjusts itself so that the voltage at the inverting input (Pin 2) is driven to virtually the same potential as the non-inverting input — which is 0 V (ground).

Since the inverting input is at 0 V but is not physically connected to ground, this point is called the Virtual Ground. The key distinction is: it is at ground potential (0 V) without being connected to the actual ground rail. This property greatly simplifies the analysis of inverting OPAMP circuits.

Virtual Ground Conditions: (1) V(−) = V(+) = 0 V | (2) No current flows into the OPAMP input terminals (because Zin = ∞). These two conditions are used to derive the gain of all OPAMP configurations.

V(−) = V(+)   and   I(in) = 0 A

The two golden rules of ideal OPAMP analysis (with negative feedback)

1.5 Offset Null Adjustment

In an ideal OPAMP, the output voltage should be exactly zero when the differential input voltage (V+ − V−) is zero. However, due to slight mismatches in the internal transistors of a real OPAMP during manufacturing, a small DC output voltage exists even when both inputs are at the same potential. This undesired output voltage is called the Output Offset Voltage.

The 741C provides an Offset Null facility through Pins 1 and 5. A 10 kΩ potentiometer is connected between Pins 1 and 5, with the wiper (middle terminal) connected to the negative supply rail (−VEE, Pin 4). By adjusting the potentiometer, the internal imbalance in the differential amplifier stage is corrected, bringing the output to exactly 0 V when the input is 0 V.

Offset Null Adjustment Circuit (741C)

```
Pin 1 ────┬──── Pin 5
              | |
          10kΩ Pot
```

```
                                |
                 GND (−VEE)  ← Wiper connected here
          Adjust potentiometer until Vout = 0V when Vin = 0V
```

- Pins 1 and 5 are the offset null terminals of the 741C
- A 10 kΩ potentiometer with its wiper tied to −VEE is the standard offset null circuit
- Offset null is adjusted at power-up with zero differential input applied
- This is important for precision DC amplifier and instrumentation applications

2. Inverting and Non-Inverting Mode — Working and Gain Calculation

2.1 Inverting Amplifier

Circuit Configuration

In the inverting amplifier configuration, the input signal (Vin) is applied to the inverting input terminal (Pin 2, the − terminal) through an input resistor Rin. The non-inverting input (Pin 3, the + terminal) is connected directly to ground. Negative feedback is provided by a feedback resistor Rf connected from the output (Pin 6) back to the inverting input (Pin 2).

Inverting Amplifier — Circuit Diagram

```
                                  Rf
                  ┌────────/\/\/\──────────────┐
                  │                            │
      Vin  ───────┤Rin─────────┬────── (−) ┐   │
                     │              OPAMP  ────┴──── Vout
                            V(−)    (+) ┘
                                        │
                                       GND

      Rin = Input Resistor     Rf = Feedback Resistor
```

Working Principle

Since the non-inverting input (V+) is grounded, V+ = 0 V. By the virtual ground concept, V− = V+ = 0 V. This means the inverting input (Pin 2) is held at virtual ground (0 V) by the negative feedback action of the OPAMP.

Since V− = 0 V and Vin is applied at the left end of Rin, the current through Rin is:

I1 = (Vin − V−) / Rin = (Vin − 0) / Rin = Vin / Rin

Current through input resistor Rin

Since no current enters the OPAMP input terminal (Zin = ∞), all of I1 flows through the feedback resistor Rf. The voltage at the output end of Rf, with respect to virtual ground (0 V at V−), is:

Vout = V− − I1 × Rf = 0 − (Vin / Rin) × Rf = −(Rf / Rin) × Vin

Output voltage of Inverting Amplifier

Voltage Gain (Av) of Inverting Amplifier

Av = Vout / Vin = −Rf / Rin

Inverting Amplifier Gain — the negative sign indicates 180° phase inversion

Phase Inversion: The output of the inverting amplifier is 180° out of phase with the input. If Vin is a positive sinusoid, Vout is a negative sinusoid of larger amplitude (if Rf > Rin).

Key Characteristics of Inverting Amplifier

- Gain is determined only by the ratio of external resistors Rf and Rin — independent of the internal OPAMP parameters
- The gain has a negative sign indicating 180° phase shift between input and output
- Input impedance of the inverting amplifier = Rin (not infinite, because the inverting input is held at virtual ground)
- The gain can be set to any value (< 1, = 1, or > 1) by appropriate choice of Rin and Rf
- For gain = −1 (unity gain inverter): set Rin = Rf

2.2 Non-Inverting Amplifier

Circuit Configuration

In the non-inverting amplifier configuration, the input signal (Vin) is applied directly to the non-inverting input terminal (Pin 3, the + terminal). The inverting input (Pin 2, the − terminal) is connected to the junction of a voltage divider formed by feedback resistor Rf (from output to Pin 2) and grounding resistor R1 (from Pin 2 to ground). Negative feedback is provided through Rf.

Non-Inverting Amplifier — Circuit Diagram

```
               Vin ──── (+) ┐
                OPAMP ─────────────── Vout
          (−) ─┤                      │
               │                      │
               ├──────── Rf ──────────┘
                         │
                         R1
                         │
                         GND

      R1 = Grounding Resistor    Rf = Feedback Resistor
```

Working Principle

The input voltage Vin is applied at the non-inverting input, so V+ = Vin. By the virtual short-circuit principle (a consequence of the golden rules), V− = V+ = Vin. Since no current flows into the OPAMP input (Zin = ∞), the current through R1 and Rf can be found by treating V− = Vin as a node.

The current through R1: I = Vin / R1. This same current flows through Rf (no current into Pin 2). The output voltage is:

$$V_{out} = V_- + I \times R_f = V_{in} + (V_{in} / R_1) \times R_f = V_{in} (1 + R_f / R_1)$$

Output voltage of Non-Inverting Amplifier

Voltage Gain (Av) of Non-Inverting Amplifier

$$A_v = V_{out} / V_{in} = 1 + (R_f / R_1)$$

Non-Inverting Amplifier Gain — always ≥ 1, no phase inversion

No Phase Inversion: The output of the non-inverting amplifier is in phase with the input (0° phase shift). The minimum gain is 1 (when Rf = 0 or R1 = ∞), which gives the Voltage Follower (Buffer) circuit.

Special Case: Voltage Follower (Unity Gain Buffer)

When Rf = 0 (short circuit) and R1 = ∞ (open circuit or removed), the non-inverting amplifier becomes a Voltage Follower. The output exactly follows the input: Vout = Vin, Av = 1. Despite the unity gain, the voltage follower is extremely useful because it provides very high input impedance and very low output impedance — making it an ideal impedance buffer between stages.

$$A_v = 1 + (0 / \infty) = 1 \quad \rightarrow \quad V_{out} = V_{in}$$

Voltage Follower: Rf = 0, R1 = ∞ (or Rf short-circuited)

2.3 Comparison: Inverting vs Non-Inverting Amplifier

Feature	Inverting Amplifier	Non-Inverting Amplifier
Input Terminal Used	Inverting (−) via Rin	Non-Inverting (+) directly
Gain Formula	Av = −Rf / Rin	Av = 1 + Rf / R1
Phase of Output	180° phase shift (inverted)	0° phase shift (in phase)
Minimum Gain (magnitude)	0 (when Rf = 0)	1 (when Rf = 0)
Input Impedance	Equal to Rin	Very high (near ideal)
Virtual Ground at	Inverting input (Pin 2)	Not applicable
Typical Application	Signal inversion, summers	Buffers, sensor amplifiers

3. Applications of OPAMP: Amplifier, Adder, Integrator & Differentiator

The OPAMP's versatility comes from the fact that its behaviour can be tailored entirely by the external components (resistors and capacitors) connected around it. By changing these components, the same 741C IC can function as an amplifier, adder, integrator, differentiator, comparator, oscillator, filter, and more. This section covers the four fundamental application circuits specified in the FEEE syllabus.

3.1 OPAMP as an Amplifier

The most fundamental application of an OPAMP is as a linear voltage amplifier. Both the inverting and non-inverting configurations described in Topic 2 serve as amplifiers. The closed-loop gain is set precisely and stably by the ratio of external resistors, making OPAMP amplifiers far more predictable than single-transistor amplifiers.

Inverting Amplifier (Review)

$$Av = -Rf / Rin \qquad Vout = -(Rf / Rin) \times Vin$$

Non-Inverting Amplifier (Review)

$$Av = 1 + Rf / R1 \qquad Vout = (1 + Rf / R1) \times Vin$$

Worked Example — Inverting Amplifier

Problem: Design an inverting amplifier with a gain of −10. If Rin = 10 kΩ, find Rf. Also find Vout if Vin = 0.5 V.

Step	Calculation	Result
Gain formula	Av = −Rf / Rin = −10	Rf / Rin = 10
Find Rf	Rf = 10 × Rin = 10 × 10 kΩ	Rf = 100 kΩ
Find Vout	Vout = −10 × 0.5 V	Vout = −5 V

Worked Example — Non-Inverting Amplifier

Problem: A non-inverting amplifier has R1 = 10 kΩ and Rf = 90 kΩ. Find the gain and output voltage when Vin = 0.2 V.

Step	Calculation	Result
Gain formula	$A_v = 1 + R_f/R_1 = 1 + 90/10$	$A_v = 10$
Find Vout	$V_{out} = 10 \times 0.2$	$V_{out} = 2$ V (in phase)

3.2 OPAMP as an Adder (Summing Amplifier)

Concept

The OPAMP adder (or summing amplifier) is an extension of the inverting amplifier that accepts multiple input voltages simultaneously and produces an output that is the weighted sum of all the inputs. It is based on the inverting amplifier configuration, with multiple input resistors — one for each input signal — all connected to the inverting input (−) terminal. The non-inverting input (+) is grounded.

Summing Amplifier (Adder) — Circuit Diagram

```
                V1 ──── R1 ──┐
                          |        Rf
      V2 ──── R2 ─┼──── (−) ────────────────── Vout
                       |            OPAMP
          V3 ──── R3 ──┘      (+)───GND

            R1, R2, R3 = Input resistors
               Rf = Feedback resistor
      For equal weighting: R1 = R2 = R3 = Rin
```

Working Principle

Using the virtual ground concept, the inverting input (−) is at 0 V. The currents through each input resistor are independent of each other (because the summing point is held at virtual ground). By KCL (Kirchhoff's Current Law), the total current flowing into the summing node equals the current through the feedback resistor Rf:

$$I_{total} = I_1 + I_2 + I_3 = V_1/R_1 + V_2/R_2 + V_3/R_3$$

$$V_{out} = -R_f \times (V_1/R_1 + V_2/R_2 + V_3/R_3)$$

Summing Amplifier Output Equation (general)

Special Case: Equal Input Resistors

When all input resistors are equal (R1 = R2 = R3 = Rin), the circuit becomes a unity-weighted adder:

$$V_{out} = -(R_f / R_{in}) \times (V_1 + V_2 + V_3)$$

Equal-weight Summing Amplifier (all inputs equally weighted)

If additionally Rf = Rin, the circuit produces the exact (inverted) sum of all inputs:

$$V_{out} = -(V1 + V2 + V3) \quad [\text{when } Rf = R1 = R2 = R3]$$

Unity-gain inverting adder

Applications of Adder Circuit

- Audio mixing consoles: Combining multiple audio signal channels into one output
- Digital-to-Analog Converters (DAC): Binary-weighted summing amplifiers convert digital bits to analog voltage
- Analog computers: Performing algebraic summation
- Signal averaging circuits

Worked Example — Summing Amplifier

Problem: A summing amplifier has R1 = R2 = R3 = 10 kΩ and Rf = 30 kΩ. Inputs: V1 = 1 V, V2 = 2 V, V3 = 3 V. Find Vout.

Step	Working	Value
Formula	Vout = −(Rf/Rin)(V1 + V2 + V3)	—
Rf/Rin ratio	30 kΩ / 10 kΩ	= 3
Sum of inputs	V1 + V2 + V3 = 1 + 2 + 3	= 6 V
Calculate Vout	Vout = −3 × 6	Vout = −18 V

3.3 OPAMP as an Integrator

Concept

An OPAMP integrator is a circuit that produces an output voltage proportional to the time integral of the input voltage. It is obtained by replacing the feedback resistor Rf in the inverting amplifier with a capacitor C, while keeping the input resistor Rin. The circuit performs the mathematical operation of integration — hence its name. The output continuously accumulates (integrates) the input signal over time.

OPAMP Integrator — Circuit Diagram

```
                    C (Capacitor)
          ┌───────────||──────────────┐
          │                           │
Vin ──────┤Rin──────────── (−) ┐      │
                         OPAMP ┴──────  Vout
                            (+) ─┘
                                 │
                                GND
```

```
Rin = Input Resistor     C = Feedback Capacitor
```

Working Principle

Using the virtual ground concept, the inverting input (−) is at 0 V. The current through Rin is I = Vin / Rin. This same current flows into the capacitor C (since no current enters the OPAMP terminal). The voltage across a capacitor is given by V = (1/C) ∫ I dt. Since the output is taken across the capacitor (from output to virtual ground), and considering the inverting action:

$$V_{out} = -(1 / R_{in}C) \int V_{in}\, dt$$

OPAMP Integrator Output — Vout is the time integral of Vin, scaled by −1/(RinC)

The term (RinC) is called the time constant (τ) of the integrator. A larger time constant gives a slower integration rate (smaller output for the same input).

$$\tau = R_{in} \times C \qquad \text{(Time Constant of Integrator)}$$

Unit: seconds (s)

Response to Common Input Signals

Input Waveform	Output Waveform	Reason
DC (constant) voltage	Linearly ramping (ramp) voltage	Integral of a constant = linear function of time
Square wave	Triangular wave	Integral of alternating constants = alternating ramps
Sinusoidal (sin ωt)	Cosinusoidal (−cos ωt / ωRC)	Integral of sin = −cos
Triangular wave	Sinusoidal / parabolic wave	Integral of linear = quadratic/smooth curve

Practical Limitation

A purely capacitive feedback results in infinite DC gain (the capacitor blocks DC feedback, making the OPAMP act as an open-loop amplifier at DC). This causes the output to drift and saturate due to any tiny offset voltage or bias current. To overcome this, a large resistor (Rf >> Rin, typically 10×) is connected in parallel with the capacitor. This provides DC feedback stability while having negligible effect on AC integration behaviour.

Applications of Integrator

- Waveform generation: Converts square waves to triangular waves
- Analog computers: Solving differential equations
- Signal processing: Low-pass filtering (integrator has low-pass frequency response)
- PID controllers: The 'I' (integral) term in control systems
- Ramp generators and sawtooth wave generators

3.4 OPAMP as a Differentiator

Concept

An OPAMP differentiator is a circuit that produces an output voltage proportional to the rate of change (time derivative) of the input voltage. It is obtained by replacing the input resistor Rin of the inverting amplifier with a capacitor C, while keeping the feedback resistor Rf. The circuit performs the mathematical operation of differentiation — the inverse of integration.

OPAMP Differentiator — Circuit Diagram

```
                            Rf
              ┌────────/\/\/\───────────┐
              │                         │
   Vin ───┤ C ──────── (-) ┐            │
          (Capacitor) OPAMP ────┘ ──── Vout
                        (+) ─┘
                             │
                            GND

C = Input Capacitor     Rf = Feedback Resistor
```

Working Principle

The input capacitor C is now in series with the input. The current through the capacitor depends on the rate of change of the input voltage: I = C × (dVin/dt). This current flows through the feedback resistor Rf (since the inverting input is at virtual ground and no current enters the OPAMP). The output voltage is:

$$V_{out} = -R_f \times C \times (dV_{in} / dt)$$

OPAMP Differentiator Output — Vout is proportional to the rate of change of Vin

The term (Rf × C) is the time constant of the differentiator. A larger time constant gives a larger output for the same rate of change.

Response to Common Input Signals

Input Waveform	Output Waveform	Reason
DC (constant) voltage	Zero output (0 V)	Derivative of a constant = 0
Ramp (linearly increasing)	Constant DC voltage	Derivative of a linear function = constant
Triangular wave	Square wave	Derivative of linear segments = constants
Sinusoidal (sin ωt)	Cosinusoidal (−ωRfC cos ωt)	Derivative of sin = cos

Square wave	Narrow spikes (impulses) at edges	Derivative is very large at sharp transitions

Practical Limitation

An ideal differentiator has a gain that increases linearly with frequency (gain = $\omega R_f C$). This means it amplifies high-frequency noise heavily, causing the output to be dominated by noise at high frequencies — making the circuit unstable and noisy in practice. To overcome this, a small resistor Rs is connected in series with the input capacitor C. This limits the high-frequency gain and improves stability, at the cost of slightly reduced differentiation accuracy at very high frequencies.

Applications of Differentiator

- Edge detection: Generates sharp pulses at the rising and falling edges of square waves
- Rate-of-change measurement: Detecting how fast a signal is changing (velocity from position in control systems)
- PID controllers: The 'D' (derivative) term in control systems
- Waveform shaping: Converting triangular waves to square waves
- FM demodulation in communication circuits

3.5 Comparison: All Four OPAMP Application Circuits

Feature	Amplifier	Adder	Integrator	Differentiator
Feedback element	Rf (resistor)	Rf (resistor)	C (capacitor)	Rf (resistor)
Input element	Rin (resistor)	R1,R2,R3 (resistors)	Rin (resistor)	C (capacitor)
Math operation	Scaling (×K)	Summation (Σ)	Integration (∫ dt)	Differentiation (d/dt)
Output formula	−(Rf/Rin)×Vin	−Rf(V1/R1+V2/R2...)	−(1/RC)∫Vin dt	−RC(dVin/dt)
Phase	180° inverted	180° inverted	180° inverted	180° inverted
Square → output	Square (amplified)	Sum of squares	Triangular wave	Spikes at edges
Key application	Signal gain	Audio mixing, DAC	Ramp gen, LPF	Edge detect, HPF

3.6 Formula Quick Reference

Circuit	Gain / Output Formula	Notes
Inverting Amplifier	Av = −Rf / Rin	Negative gain = 180° phase shift
Non-Inverting Amplifier	Av = 1 + Rf / R1	Gain ≥ 1, no phase inversion
Voltage Follower	Av = 1, Vout = Vin	Rf = 0, R1 = ∞

Summing Amplifier	Vout = −Rf(V1/R1 + V2/R2 + ...)	Multiple inputs, weighted sum
Integrator	Vout = −(1/RC) ∫ Vin dt	τ = RC; square in → triangle out
Differentiator	Vout = −RC (dVin/dt)	τ = RC; triangle in → square out

End of Chapter: Overview of Analog Circuits (OPAMP)
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