Sirindhorn International Institute of Technology

Thammasat University at Rangsit

School of Information, Computer and Communication Technology

COURSE : ECS 204 Basic Electrical Engineering Lab

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EXPERIMENT : 08 Operational Amplifiers II

I. OBJECTIVE

To study the use of operational amplifier in converters and integrator.

II. BASIC INFORMATION

II.1 Op-Amp 741

1. The pin details of op amp 741 are shown in Figure 1 below.

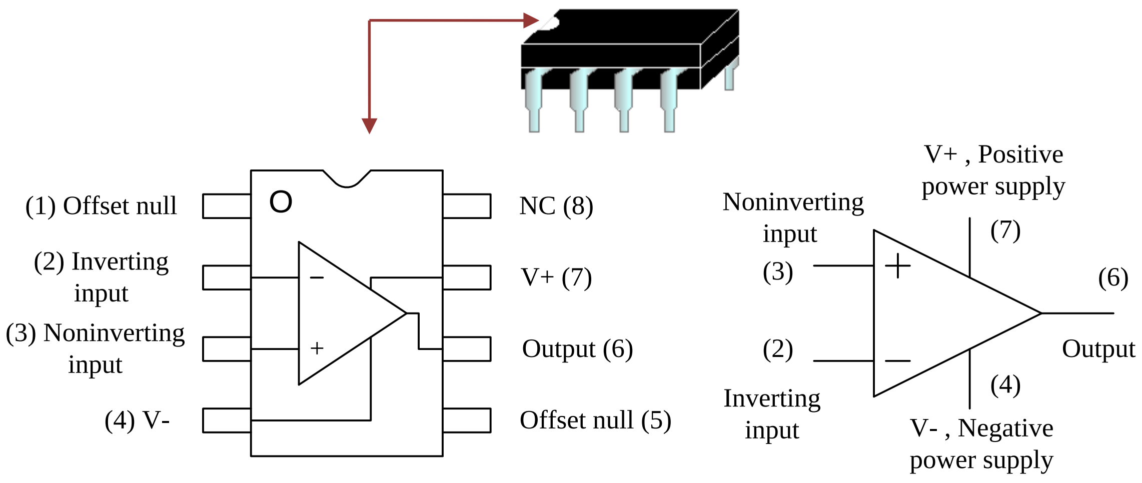


Figure 1: Pin details and configuration of IC 741.

Caution: **An op-amp must be treated with special care**. They are powerful but can be easily damaged from wrong circuit wiring. In particular it is abusive to apply AC-signal voltages to the input terminals before providing the power supply (or fully powering up the device), or to exceed certain maximum limits. Therefore, for each section of this experiment, follow the following steps.

i. Set up the circuit with all signal sources turned off.

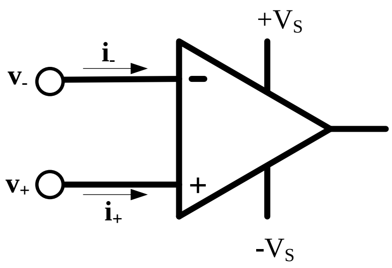
ii. Double-check your connection.

iii. Enable the power supply (i.e. power up the op amp device).

iv. Turn up the signal source.

v. Op amps can also be damaged if their outputs are shorted to ground or to the power supply. Please also be very careful with wiring.

2. Two important characteristics of the ideal op amp are
   1) The currents into both input terminals are zero:
   $$i_+ = i_- = 0\,.$$
   2) The voltage across the input terminals is negligibly small:
   $$v_+ \approx v_-\,.$$
   Remark: Do not assume that $v_+ = v_- = 0$!



II.2 Voltage-to-Current Converter and Current-to-Voltage Converter

1. The voltage-to-current and current-to-voltage converters are used in electronic voltmeters and ammeters, respectively.
2. The **voltage-to-current converter**, as shown in Figure 2, produces an output current that depends on the input voltage and the resistor R. In particular, the output current is given by
   $$I_{out} = V_i/R$$
   independent of the loading resistance R_L.
3. The **current-to-voltage converter**, as shown in Figure 3, produces an output voltage that depends on the input current and the resistor R. In particular, the output voltage is given by
   $$V_o = -I_{in}R$$
   independent of the loading resistance R_L.

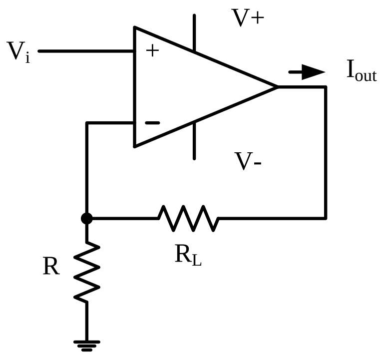


Figure 2**:** Voltage-to-current converter.

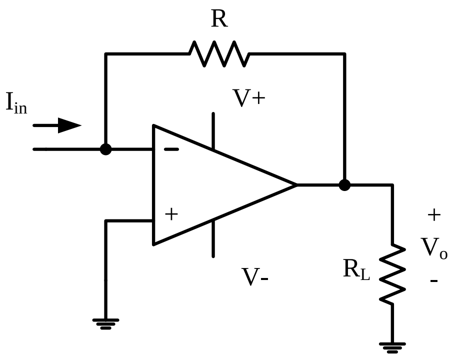


Figure 3: Current-to-voltage converter.

II.3 Inverting Integrator

1. An inverting integrator is shown in Figure 4.

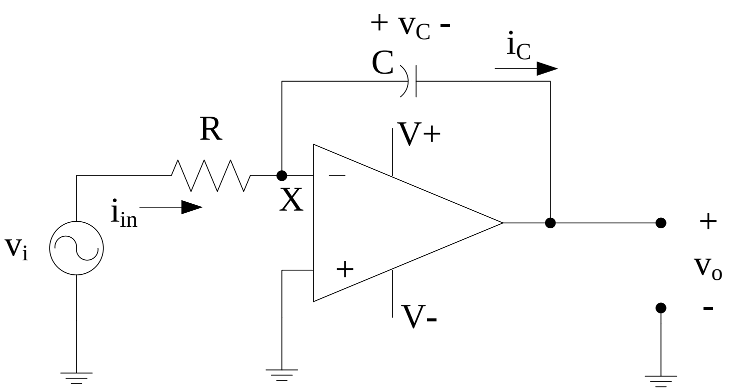


Figure 4: Inverting Integrator

Since no current enters the inverting input of an ideal op amp, all input currents must flow through the capacitor. Thus, $i_C = i_{in}$. Moreover, for ideal op amp, we know that the voltage at the two input terminals must be the same. Therefore, $v_X = 0$. This gives $i_{in} = v_i/R$. Recall the relationship between the time-dependent current and voltage for the capacitor:

$$i_C(t) = C\frac{d}{dt}v_C(t).$$

In this case, the current through the capacitor is

$$i_C(t) = i_{\text{in}}(t) = \frac{v_i(t)}{R}$$

and the voltage across the capacitor is

$$v_C(t) = v_X - v_o(t) = -v_o(t).$$

Hence,

$$\frac{v_i(t)}{R} = -C\frac{d}{dt}v_o(t).$$

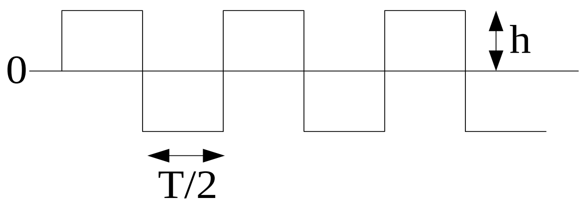
The output voltage then has the following form:

$$v_o(t) = v_o(0) - \frac{1}{RC}\int_0^t v_i(\tau)\,d\tau,$$

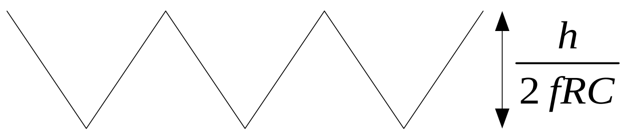
where $v_o(0)$ is the initial value of the output voltage. Note that the change in the output voltage (when considered at two time instants t_1 and t_2) is inversely proportional to the integration of the input voltage.

$$v_o(t_2) - v_o(t_1) = -\frac{1}{RC}\int_{t_1}^{t_2} v_i(t)\,dt.$$

Suppose the input voltage waveform v_i is a square wave with frequency f and peak-to-peak voltage $2h$ as shown in Figure 5a.



(a) Input waveform



(b) Output waveform

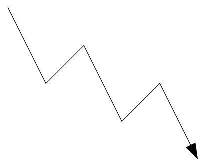
Figure 5: Input and corresponding output waveform to the integrating amplifier in Figure 4.

For half of the period, the input is fixed at $+h$. During this time, the output will decrease. At the end of this interval, the total decrease is

$$\frac{1}{RC}h \times \frac{T}{2} = \frac{h}{2fRC}.$$

Similarly, the output will increase during the time that the input is fixed at $-h$. Because input has equal areas above and below the ground level, the decrease amount is the same as the increase amount and we see a triangular waveform at the output. The peak-to-peak voltage is $h/\left(2\,fRC\right)$ as shown in Figure 5b. In conclusion, **when a square wave drives an op amp integrator, the output is a triangular wave**.

Remark: For the circuit in Figure 4, an input with nonzero mean (DC offset) can saturate the op amp. To see this, suppose the range of the square wave input is from -1 to 2 V. Then, during each period of the input, the output will have a $\frac{2}{2\,fRC}$ decrease and a $\frac{1}{2\,fRC}$ increase.



Because the amount of decrease is greater, the output will accumulate this difference during each period. It will keep decreasing until it saturates the op amp.

2. The analysis provided earlier is performed in time domain. Alternatively, we can analyze the integrator in Figure 4 in frequency domain via steady-state AC analysis. In particular, suppose the input is sinusoidal with peak V_i and frequency f.

   In AC analysis, we use impedance. The relationship between the current and voltage for the capacitor is

$$V_C = I_C \times Z_C = I_C \times \frac{1}{j\omega C}.$$

   For ideal op amp, we again have

$$I_C = I_{\text{in}} = \frac{V_i}{R}$$

   and

$$V_C = V_X - V_o = -V_o.$$

   Hence,

$$V_o = -V_C = -I_C \times \frac{1}{j\omega C} = -\left(\frac{V_i}{R}\right) \times \frac{1}{j\omega C}.$$

   Therefore, the gain at frequency f is

$$-\frac{1}{j2\pi\, fRC}.$$

   In particular, the gain at $f = 0$ is unbounded.

   Recall, from your calculus class, that you can decompose a periodic waveform into a sum of weighted sinusoidal waveforms. If your waveform has a nonzero average, then you have a constant in your sum as well. This constant is the **DC offset**. Our frequency-domain analysis above shows that if the DC offset is nonzero, it will be (theoretically) amplified by an infinite gain! This will saturate the op amp.

3. In practical circuit, a resistor R_p is usually shunted across the capacitor as shown in Figure 6. In this case,

$$V_C = I_{\text{in}} \times \left(Z_C // R_p\right) = \frac{V_i}{R} \frac{1}{j\omega C + \frac{1}{R_p}} = \frac{V_i}{R} \frac{R_p}{j\omega R_p C + 1}.$$

So,

$$V_o = -V_C = -\frac{V_i}{R} \frac{R_p}{j\omega R_p C + 1}$$

and the gain is

$$\frac{V_o}{V_i} = -\frac{1}{R} \frac{R_p}{j\omega R_p C + 1}.$$

With the added R_p, at $f = 0$, the gain is finite.

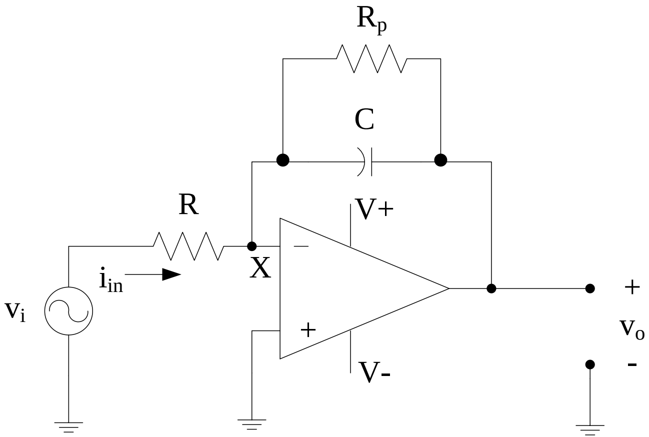


Figure 6: Inverting Integrator with shunt resistor

Large R_p is used so that the overall operation of the circuit is not too different from the original integrating amplifier.

One important effect of adding R_p is that the **output will *not* be triangular anymore**. You will still observe an output that is very similar to a triangular waveform if the product $R_p C$ is large compared to the half-period time T/2.

It can be shown that if the input is a zero-mean square wave with frequency f and peak-to-peak voltage $2h$ then, the output will be zero-mean waveform with peak-to-peak voltage

$$2h\frac{Rp}{R}\frac{1-r}{1+r},$$

where $r = \exp\left(-\frac{1}{2\ fR_pC}\right)$.

III. MATERIALS REQUIRED

Power supplies:

± 12V, DC, regulated

Variable 0-15 V

Equipment:

Oscilloscope

Function generator

Multi-meter

Resistors:

two 1-kΩ	one 100-kΩ	one 12-kΩ

Semiconductor:

one op amp 741

Capacitors:

one 0.001 μF	one 0.01 μF	one 0.047 μF

IV PROCEDIRE

Part A: Voltage-to-current converter

1. Connect the circuit of Figure 7.
   Remark:
   (1) Recall how to generate the +12V and -12V from the previous experiment.
   (2) Do not forget to put all the grounds at the same node.
2. Adjust voltage supply V_{in} according to the value listed in Table 8-1.
   Record the corresponding I_{out}.

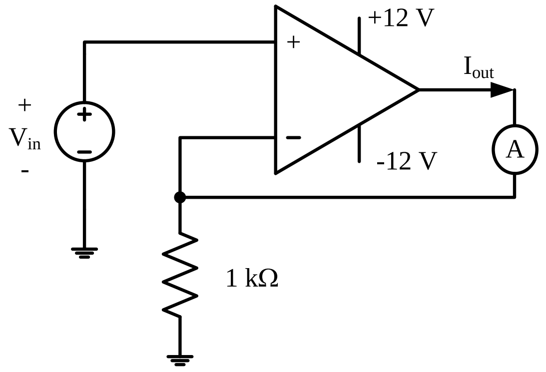


Figure 7**:** Voltage-to-current converter.

Part B: Current-to-voltage converter

1. Connect the circuit of Figure 8.
2. Adjust the voltage supply V_{in} such that the current i_{in} according to Table 8-2 is obtained.
3. Measure V_{out} and record the result in Table 8-2.

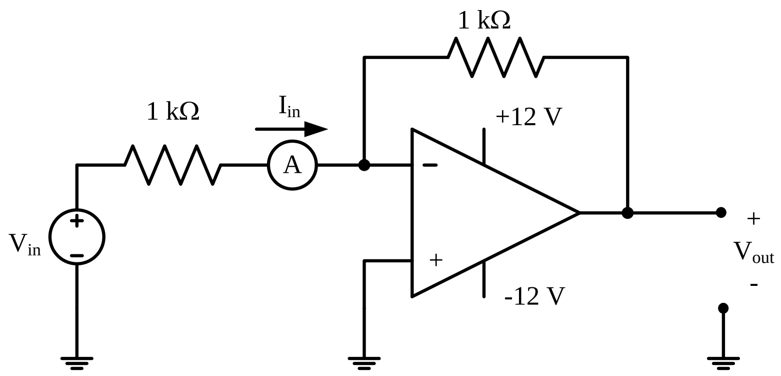


Figure 8: Current-to-voltage converter.

Caution: Do not connect the output directly to the ground.

Part C: Op amp Integrator

1. Connect the circuit shown in Figure 9.
2. Observe $v_{in}(t)$ and $v_{out}(t)$ of the circuit for several values of C and record the results as prescribed in Table 8-3.
   Note that you can use different volts/div for v_{in} and v_{out}.

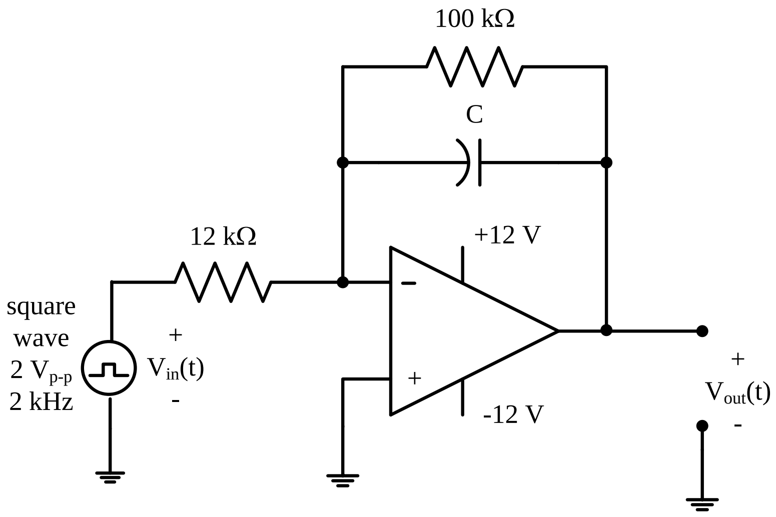


Figure 9: Op amp integrator.

TABLE 8-1: Voltage-to-current converter

R = _______________

V_{in}, V		I_{out}, mA
1		
3		
6		
10		

TA's Signature: __________________________

TABLE 8-2: Current-to-voltage converter

R = _______________

I_{in}, mA		V_{out}, V
1		
3		
6		
10		

TA's Signature: __________________________

TABLE 8-3: Op amp integrator

C = 0.047 μF	Waveforms: time/div = ____________
V_{in} = _______$V_{p\text{-}p}$ $V_{DC,in}$ = _______	volts/div = ____________
V_{out} = ______$V_{p\text{-}p}$ $V_{DC,out}$ = _______	volts/div = ____________

TA's Signature: ___________________________

C = 0.01 μF	Waveforms: time/div = ____________
V_{in} = _______$V_{p\text{-}p}$ $V_{DC,in}$ = _______	volts/div = ____________
V_{out} = ______$V_{p\text{-}p}$ $V_{DC,out}$ = _______	volts/div = ____________

C = 0.001 μF	Waveforms: time/div = ____________
V_{in} = _______$V_{p\text{-}p}$ $V_{DC,in}$ = _______	volts/div = ____________
V_{out} = ______$V_{p\text{-}p}$ $V_{DC,out}$ = _______	volts/div = ____________

TA's Signature: ___________________________

QUESTIONS

1. Find the output $V_o(t)$ of the integrator shown in Fig. Q-1 which responses to the input shown in Fig. Q-2. Assume R = 10 kΩ, C = 10 nF and $v_o(0) = 0$.

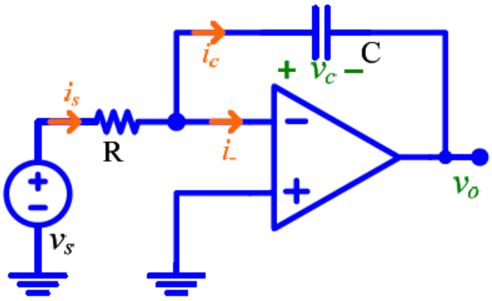


Figure Q-1: An integrator

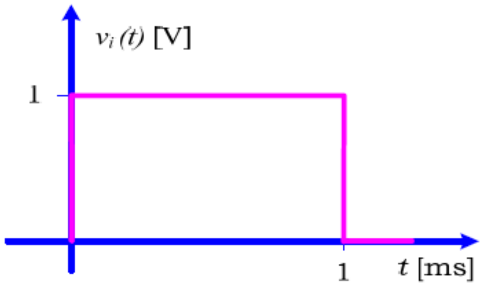


Figure Q-2: Step input

(a) -10t for $0 \leq t \leq 1$ms
(b) -100t for $0 \leq t \leq 1$ms
(c) -1000t for $0 \leq t \leq 1$ms
(d) -10000t for $0 \leq t \leq 1$ms
(e) None of above.

2. If a _____ voltage is present at the input of the integrator op amp, the output voltage will be a ______ slope output.

(a) negative, negative
(b) positive, positive
(c) negative, positive
(d) positive, zero
(e) None of above.

3. Consider an inverting integrator shown in Figure Q-1. The input $v_s(t)$ is plotted in Figure Q-3. Suppose $v_o(0)$ = 0 and T = RC. Plot $v_o(t)$

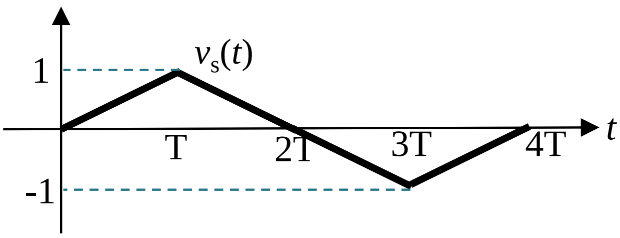


Figure Q-3: Triangular Input