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DIFFERENTIATOR

A differential amplifier op-amp is a circuit configuration that amplifies only the difference between two input signals (and) while rejecting common-mode signals (noise). Using an op-amp with resistors, it outputs the difference scaled by a gain factor, commonly acting as a subtractor. It is essential for precision signal processing, sensor measurement, and noise reduction. Let’s start by looking at the standard layout of an operational amplifier differentiator circuit.

The active differentiator circuit can be obtained by exchanging the positions of R and C in the basic active integrator circuit. The op-amp differentiator circuit is shown in the Fig. 2.30.1.

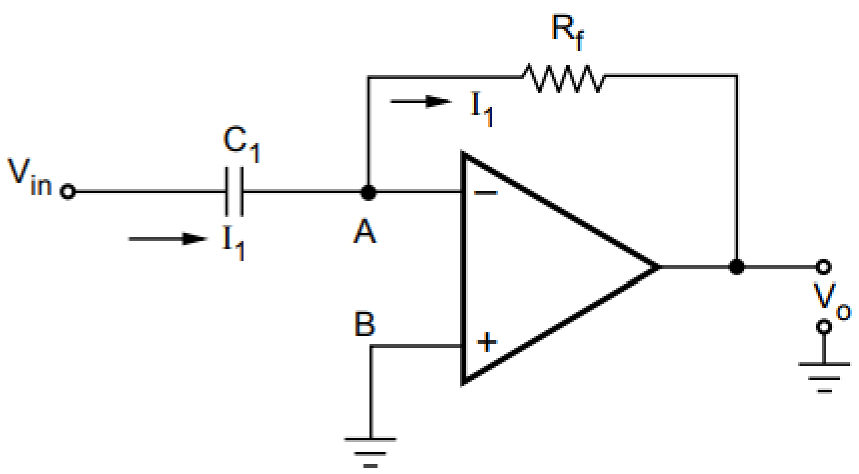

Fig. 2.30.1 Op-amp differentiator

The node B is grounded. The node A is also at the ground potential hence $V_A = 0$.

As input current of op-amp is zero, entire current I flows through the resistance Rf.

From the input side we can write,

$$I_1 = C_1 \frac{d(V_{in} - V_A)}{dt} = C_1 \frac{dV_{in}}{dt} \quad \dots (2.30.1)$$

From the output side we can write,

$$I = \frac{(V_A - V_o)}{R_f} = -\frac{V_o}{R_f} \quad \dots (2.30.2)$$

Equating the two equations,

$$C_1 \frac{dV_{in}}{dt} = -\frac{V_o}{R_f} \quad \dots (2.30.3)$$

$$\boxed{V_o = -C_1 R_f \frac{dV_{in}}{dt}} \quad \dots (2.30.4)$$

The equation shows that the output is C_1R_f times the differentiation of the input and product C_1R_f is called time constant of the differentiator.

The negative sign indicates that there is a phase shift of 180° between input and output. The main advantage of such an active differentiator is the small time constant required for differentiation.

By Miller's theorem, the effective resistance between input node A and ground becomes $R_f / 1 + A_v \approx R_f / A_v$ where A_v is the gain of the op-amp which is very large. Hence effective Rf becomes very very small and hence the condition $R_f C_1 << T$ gets satisfied at all the frequencies.

In practice a resistance $R_{comp} = R_f$ is connected to the non-inverting terminal to provide the bias compensation. This is shown in the Fig. 2.30.2.

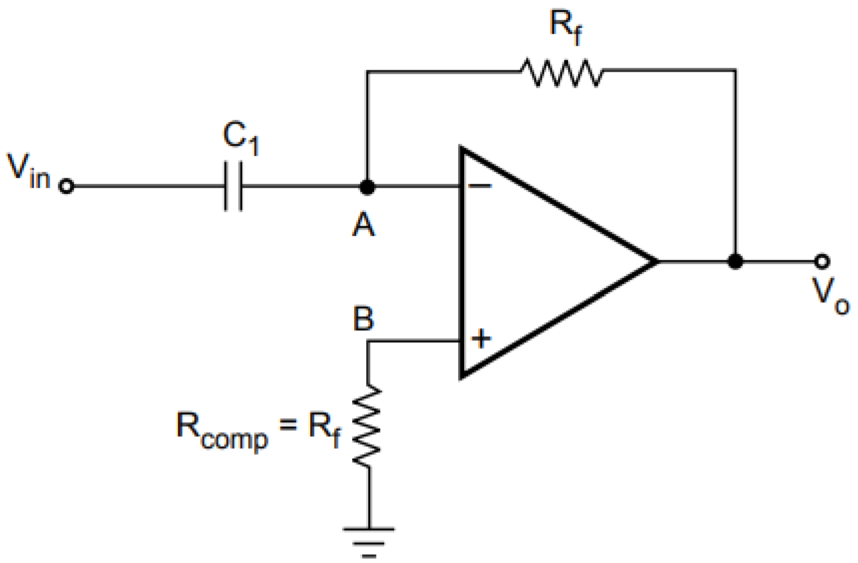

Fig. 2.30.2 Differentiator with bias compensation

Input and Output Waveforms

Let us study the output waveforms, for various input signals.

For simplicity of understanding, assume that the values of R_f and C_1 are selected to have time constant (R_fC_1) as unity.

i) Step input signal

Let the input waveform is of step type with a magnitude of A units. Mathematically it is expressed as,

V_{in} (t) = A for t ≥ 0 ... (2.30.5)

Now mathematically, the output of the differentiator must be,

Vo (t) = - dV_{in} / dt = - d(A) / dt = 0 …. (2.30.6)

This is because A is constant.

Actually the step input takes a finite time to rise from 0 to A volts.

Due to this finite time, the differentiator output is not zero but appears in the form of a spike at t = 0.

As the circuit acts as an inverting differentiator, the negative going spike or impulse appears at t = 0 and after that output remains zero.

Both input and output waveforms of the differentiator with a step input, are shown in the Fig. 2.30.3.

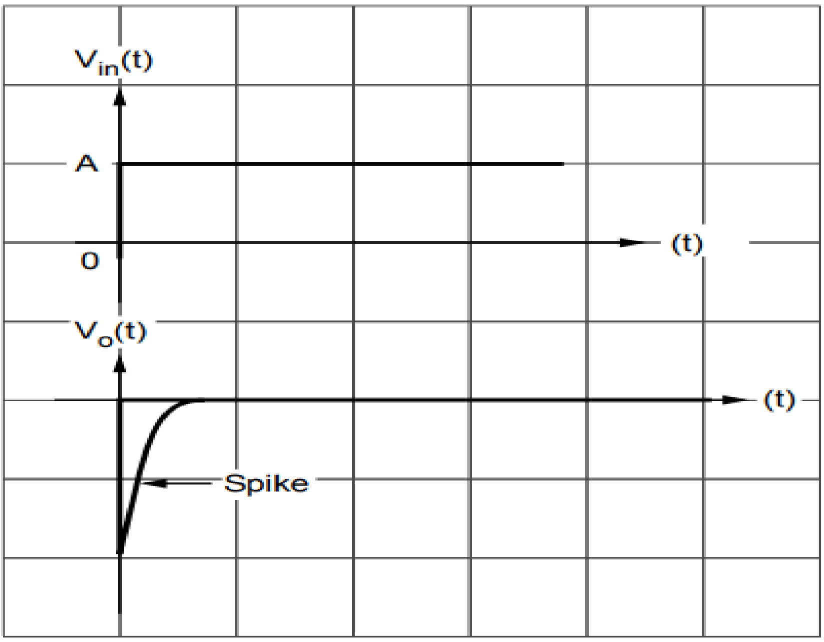

Fig. 2.30.3 Input and output for step input

Square wave input signal

Input and output for square wave input

The square wave is made of steps i.e. step of A volts from t = 0 to t = T/2, while a step of -A volts from t = T/2tot = T and so on.

Mathematically it can be expressed as,

V_{in} (t) = A   0 < t < T/2

= - A T/2 < t < T … (2.30.7)

The differentiator behaves similar to its behaviour to step input.

For positive going impulse, the output shows negative going impulse and for negative going input, the output shows positive going impulse.

Hence the total output for the square wave input is in the form of train of impulses or spikes.

The input and output waveforms are shown in the Fig. 2.30.4

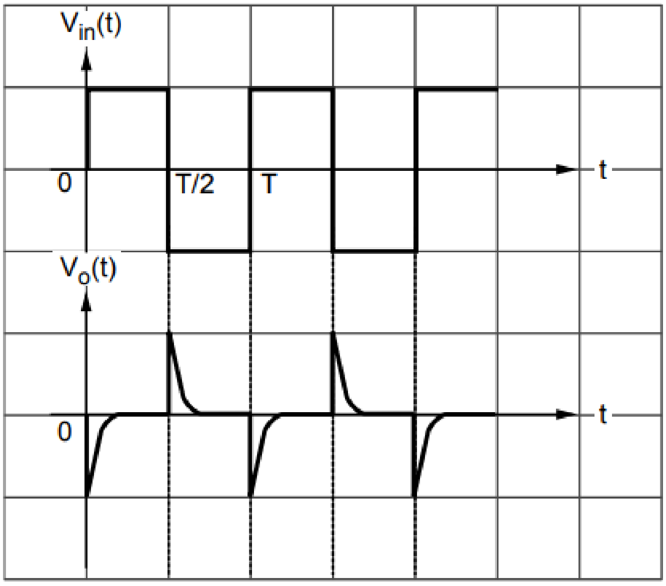

Fig. 2.30.4 Input and output for square wave input

iii) Sine wave input

Let the input waveform be purely

sinusoidal with a frequency of ω rad/sec. Mathematically it can be expressed as,

$V_{in}(t) = V_m \sin \omega t$ …. (2.30.8)

where V_m is the amplitude of the sine wave and T is the period of the waveform. Let us find out the expression for the output.

$$V_o(t) = \frac{-d\,V_{in}(t)}{dt} \quad \text{for} \quad R_f C_1 = 1 = -\frac{d}{dt}(V_m \sin \omega t)$$

$$\therefore \quad \boxed{V_o(t) = -V_m \cdot \omega \cos \omega t}$$

So at $t = 0, \quad V_o(t) = -V_m \omega$

$$t = \frac{T}{4}, \quad V_o(t) = 0$$

$$t = \frac{T}{2}, \quad V_o(t) = +V_m \omega$$

and so on.

Thus the output of the differentiator is a cosine waveform, for a sine wave input. The input and output waveform is shown in the Fig. 2.30.5.

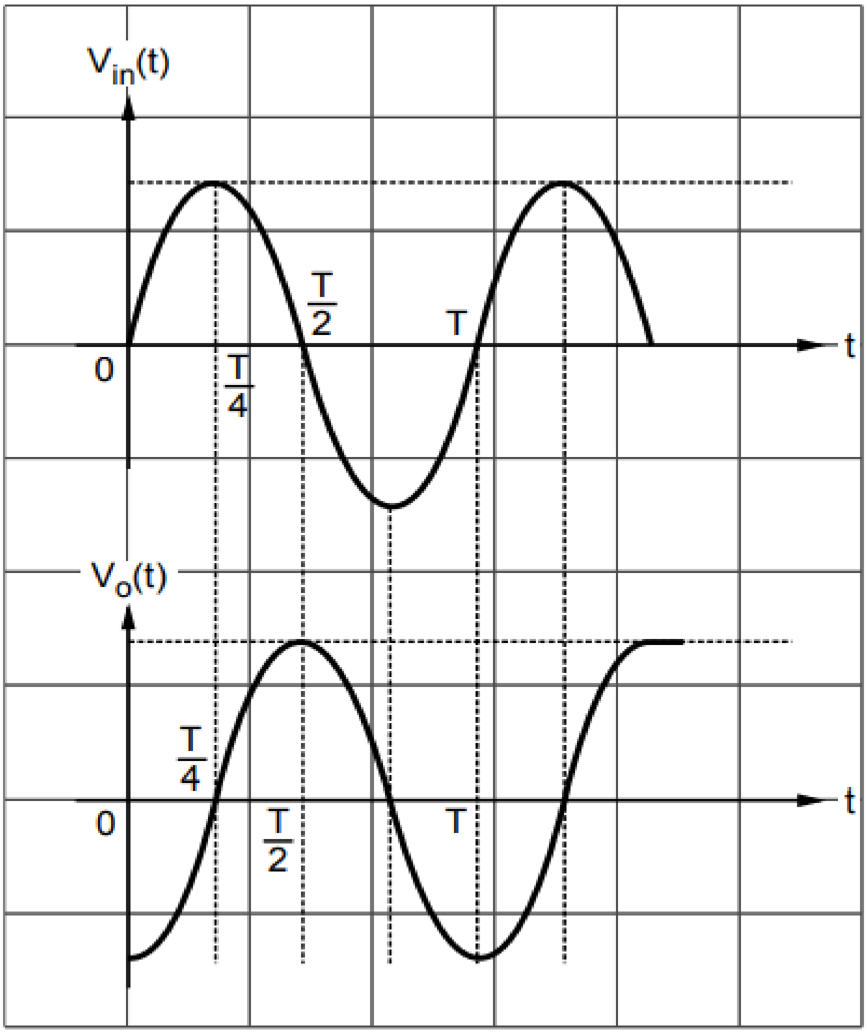

Fig. 2.30.5 Input and output for sine wave input

Disadvantages of Differentiator

The gain of the differentiator increases as frequency increases. Thus at some high frequency, the differentiator may become unstable and break into the oscillations. There is possibility that op-amp may go into the saturation.

Also the input impedance $X_{c1} = (1 / 2\pi f C_1)$ decreases as frequency increases. This makes the circuit very much sensitive to the noise. Thus when such noise gets amplified due to high gain at high frequency, noise may completely override the differentiated output.

Hence the differentiator circuit suffers from the limitations on its stability and noise problems, at high frequencies. These problems can be corrected using some additional parameters in the basic differentiator circuit. Such a differentiator circuit is called