Bandwidth with Feedback

The bandwidth of an amplifier is defined as the band (range) of frequencies for which the gain remains constant. For op-amp, the gain-bandwidth product is constant. Figure 5 shows the open-loop gain versus frequency curve of the 741C op-amp. From this curve for a gain of 200000, the bandwidth is approximately 5 Hz; or the gain-bandwidth product is (200000 x 5 Hz) = 1 MHz. On the other extreme, the bandwidth is approximately 1 MHz when the gain is 1.

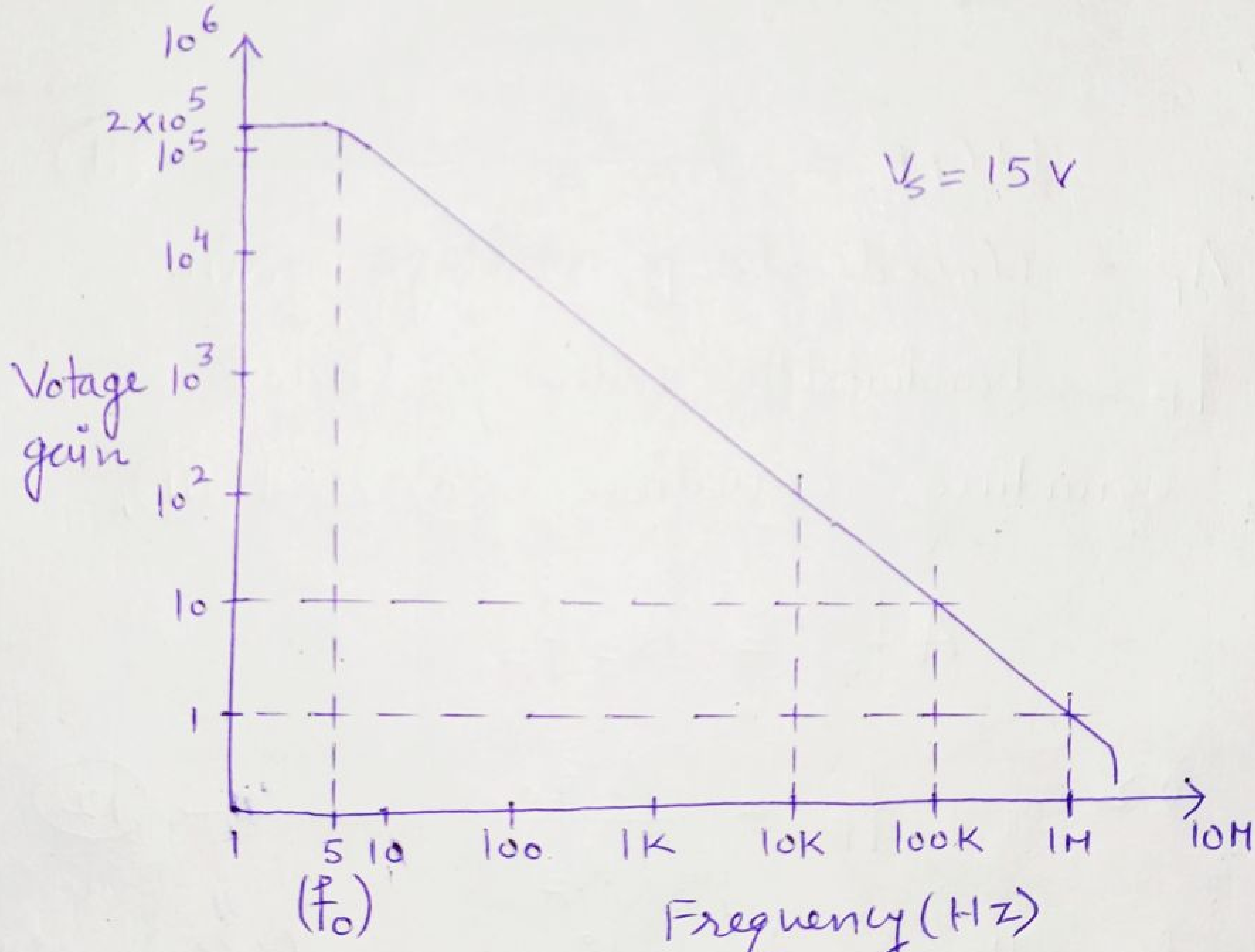

Figure 5. Open loop gain versus frequency curve of the 741C.

Op-amp's have just one break frequency. Break frequency is the frequency at which the gain A is 3 dB down from its value at 0Hz. We will denote it by f_o. For The case of 741C, 5 Hz is the break frequency.

On the other hand, the frequency at which the gain equals 1 is known as the unity gain bandwidth (UGB). Since for an op-amp with a single break frequency f_o, the gain-bandwidth product is constant, and equal to the unity gain band width (UGB), we can write,

$$UGB = A f_o \qquad \text{——— (10)}$$

where A = open-loop voltage gain
f_o = break-frequency of an op-amp

or, alternatively, only for a single break frequency op-amp,

$$UGB = A_F f_F \qquad \text{——— (11)}$$

where A_F = closed-loop voltage gain
f_F = bandwidth with feedback

Therefore, equating equation (10) and (11),

$$A f_o = A_F f_F$$

or
$$f_F = \frac{A f_o}{A_F} \qquad \text{——— (12)}$$

However, for the noninverting amplifier with feedback,

$$A_F = \frac{A}{1 + AB}$$

Therefore, substituting the value of A_F in equation (12), we get

$$f_F = \frac{A f_o}{A/(1+AB)}$$

or
$$f_F = f_o (1 + AB) \qquad \text{——— (13)}$$

Note: If negative feedback is used in noninverting amplifier, the gain A decreases to $A/(1+AB)$ and open-loop bandwidth f_o increases to $f_o(1+AB)$.

Total Output Offset Voltage with Feedback

In an op-amp when the input is zero, the output is also expected to be zero. However, because of the effect of the input offset voltage and current, the output is significantly larger. It is so because the open loop high gain aggravates the effect of input offset voltage and current at the output. We call this enhanced output voltage the total output offset voltage V_{OOT}. In an open-loop op-amp, the total output offset voltage is equal to either the positive or negative saturation voltage.

Since with feedback the gain of the noninverting amplifier changes from A to $A/(1+AB)$, the total output offset voltage with feedback must also be $1/(1+AB)$ times the voltage without feedback. That is,

$$\text{Total output offset voltage with feedback} = \frac{\text{Total output offset voltage without feedback}}{1+AB}$$

$$\text{or,} \quad V_{OOT} = \frac{\pm V_{sat}}{1+AB} \qquad (14)$$

where $1/(1+AB)$ is always less than 1 and

$\pm V_{sat}$ = Saturation voltages, the maximum voltages the output of an op-amp can reach.

From this analysis it is clear that the noninverting amplifier with feedback exhibits the characteristics of the perfect voltage amplifier. That is, it has very high input resistance, very low output resistance, stable voltage gain, large bandwidth and very little (ideally zero) output offset voltage.

Voltage Follower

The lowest gain that can be obtained from a non-inverting amplifier with feedback is 1. When the noninverting amplifier is configured for unity gain, it is called a "Voltage Follower", because the output voltage is equal to and in phase with the input. In other words, in the voltage follower, the output follows the input.

The voltage follower is preferred because it has much higher input resistance and the output amplitude is exactly equal to the input.

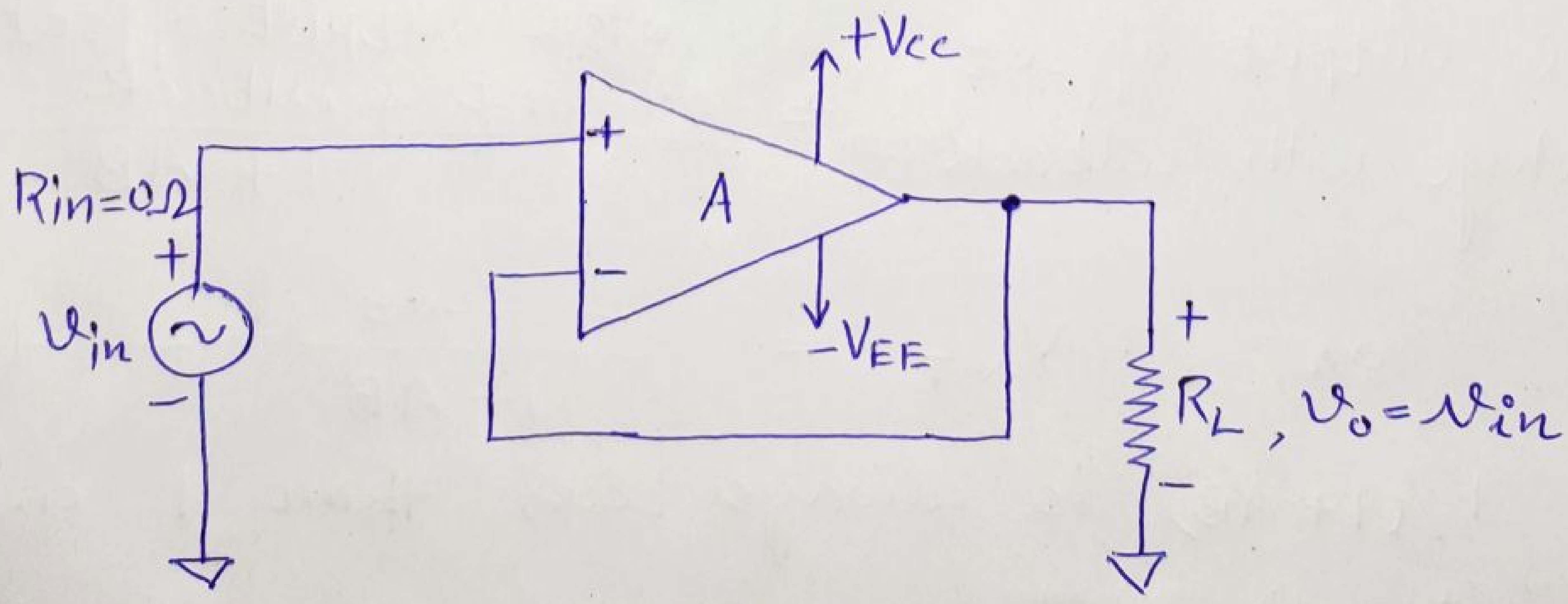

Figure 6. Voltage Follower

To obtain the voltage follower from noninverting amplifier, simply open R_1 and short R_F. The resulting circuit is shown in Figure 6. In this Figure, all the output voltage is fed back into the inverting terminal of the op-amp, consequently, the gain of the feedback circuit is 1 ($B = A_F = 1$).

The applicable formulas are

$$A_F = 1$$

$$R_{iF} = A R_i$$

$$R_{oF} = \frac{R_o}{A}$$

$$f_F = A f_o$$

$$V_{ooT} = \frac{\pm V_{sat}}{A}$$

since $(1+A) \cong A$

The voltage follower is also called a noninverting buffer because, when placed between two networks, it removes the loading on the first network.

Q1. An op-amp having the following parameters is connected as a noninverting amplifier with $R_1 = 1\,K\Omega$ and $R_F = 10\,K\Omega$; $A = 200000$; $R_i = 2\,M\Omega$; $R_o = 75\,\Omega$; $f_o \cong 5\,Hz$; supply voltages $= \pm 15\,V$; output voltage swing $= \pm 13\,V$.

Compute the values of A_F, R_{iF}, R_{oF}, f_F and V_{ooT}.

Solution: Let us first calculate the value of B. Then the closed-loop parameters A_F, R_{iF}, R_{oF}, and V_{OOT} can be obtained.

$$B = \frac{R_1}{R_1 + R_F} = \frac{1\,K\Omega}{1\,K\Omega + 10\,K\Omega} = \frac{1}{11}$$

Now, $$1 + AB = 1 + \frac{200000}{11} = 18182.8$$

$$\therefore\ A_F = \frac{A}{1+AB} = \frac{200000}{18182.8} = 10.99$$

$$R_{iF} = 2 \times 10^6 (18182.8) = 36.4\,G\Omega$$

[Note: $R_{iF} = R_i(1+AB)$]

$$R_{oF} = \frac{R_o}{1+AB} = \frac{75}{18182.8} = 4.12\,m\Omega$$

$$f_F = f_o(1+AB) = 5(18182.8)$$

$$f_F = 90.9\,KHz$$

and $$V_{OOT} = \frac{\pm V_{sat}}{1+AB} = \frac{\pm 13}{18182.8} = \pm 0.715\,mV$$

[Note Output voltage swing $= \pm V_{sat} = \pm 13V$]

In the above example, the voltage gain calculated using the exact equation is 10.99.

Note: $$A_F = \frac{A}{1+AB} \quad \text{(exact)}$$

$$A_F = 1 + \frac{R_F}{R_1} \quad \text{(ideal)}$$

The gain would have been 11 if we had used the ideal voltage gain equation. Thus, the difference error is very small (0.09%) and can be ignored. Therefore, for all practical purposes, we may use the ideal voltage-gain equation.

Q2. An op-amp having the following parameters is connected as a noninverting amplifier. The op-amp is working as voltage follower. Compute the values of A_F, R_{iF}, R_{oF}, f_F and V_{OOT} if;

$$A = 200000$$

$$R_i = 2\ M\Omega$$

$$R_o = 75\ \Omega$$

$$f_o = 5\ Hz$$

$$\text{supply voltage} = \pm 15V$$

$$\text{output voltage swing} = \pm 13V$$

Solution: For the voltage follower, $B = 1$;

therefore $$1 + AB \cong 200000$$

$$\therefore \quad A_F = 1$$

$$R_{iF} = AR_i = 2 \times 10^6 \times 200000$$

$$R_{iF} = 400\ G\Omega$$

$$R_{oF} = \frac{R_o}{A} = \frac{75}{200000} = 0.375\ m\Omega$$

$$f_F = f_o \cdot A = 5 \times 200000 = 1\ MHz$$

$$V_{OOT} = \frac{\pm 13\,V}{200000} = \frac{\pm V_{sat}}{A}$$

$$V_{OOT} = \pm 65\,\mu V$$
