RANGKAIAN ELEKTRONIKA II

Penguat Operasional

Mifta Nur Farid, S.T., M.T.
miftanurfarid@lecturer.itk.ac.id

Teknik Elektro
Institut Teknologi Kalimantan
Balikpapan, Indonesia

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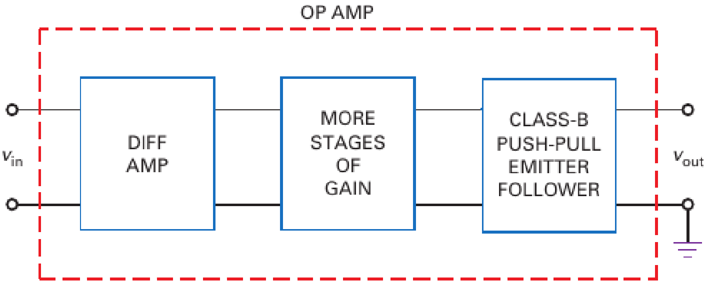
Sub-CPMK

Mahasiswa mampu menganalisis rangkaian penguat operasional (C4, P3, A3)

Bahan Kajian

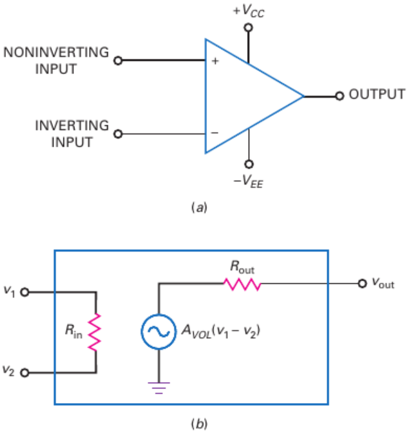
1. Konsep dasar penguat operasional;
2. Inverting amplifier;
3. Noninverting amplifier;
4. The Summing Amplifier;
5. Voltage Follower.

Pengantar



Gambar. 1: Blok diagram sebuah op amp

Pengantar



Gambar. 2: (a) Simbol dari op amp dan (b) rangkaian ekivalen dari op amp

Pengantar

Summary Table 16-1	Typical Op-Amp Characteristics			
Quantity	**Symbol**	**Ideal**	**LM741C**	**LF157A**
Open-loop voltage gain	A_{VOL}	Infinite	100,000	200,000
Unity-gain frequency	f_{unity}	Infinite	1 MHz	20 MHz
Input resistance	R_{in}	Infinite	2 MΩ	10^{12} Ω
Output resistance	R_{out}	Zero	75 Ω	100 Ω
Input bias current	$I_{in(bias)}$	Zero	80 nA	30 pA
Input offset current	$I_{in(off)}$	Zero	20 nA	3 pA
Input offset voltage	$V_{in(off)}$	Zero	2 mV	1 mV
Common-mode rejection ratio	CMRR	Infinite	90 dB	100 dB

Gambar. 3: Perbandingan karakteristik op amp ideal dan op amp standar

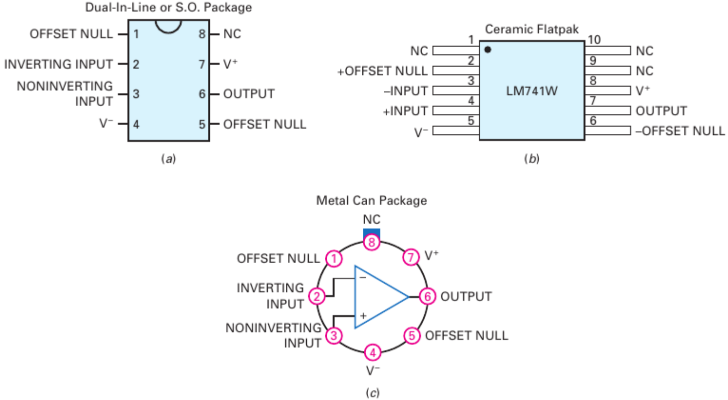
Op Amp 741

- Monolitic amp μA709 tahun 1965 oleh Fairchild Semiconductor
- μA709 memiliki kekurangan $\rightarrow$ dibuatlah μA741
- Banyak manufaktur yang membuat μA741:
  - ON Semiconductor: MC1741
  - Texas Instruments: LM741
  - Analog Devices: AD741.
- Istilah umumnya op amp 741

Standar Industri

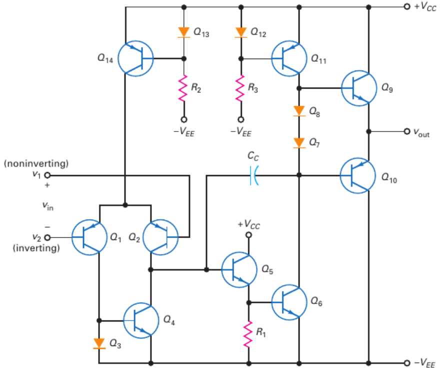
- Beberapa versi: 741, 741A, 741C, 741E, dan 741N
- Bergantung pada karakteristiknya (voltage gain, temp. range, noise level, dll)
- 741C (C = *Commercial grade*) $\rightarrow$ sedikit lebih murah dan paling banyak digunakan
- $A_{VOL} = 100000$, $z_{in} = 2\ \mathrm{M}\Omega$, $z_{o}ut = 75\ \Omega$

Standar Industri



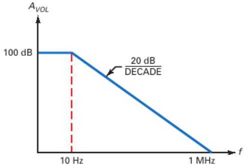
Gambar. 4: Op amp 741 pinouts (a) dual-in-line, (b) ceramic flatpak, (c) metal can

Rangkaian Ekivalen dari Op Amp 741



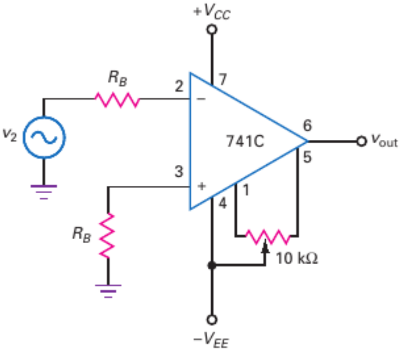
Gambar. 5: Rangkaian ekivalen dari op amp 741

- Input diff amp
- Final Stage
- Active Loading
- Frequency Compensation
  $C_{in(M)} = (A_v + 1)C_c$



Gambar. 6: Bode plot A_{VOL} 741C ideal

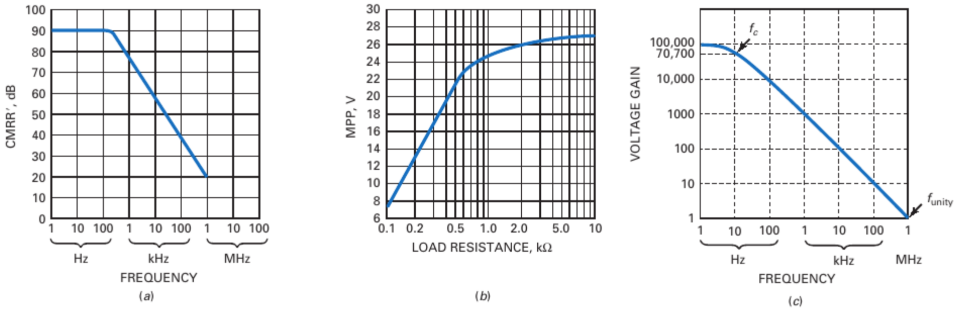
Bias & Offset



Gambar. 7: Penggunaan compensation dan nulling 741C

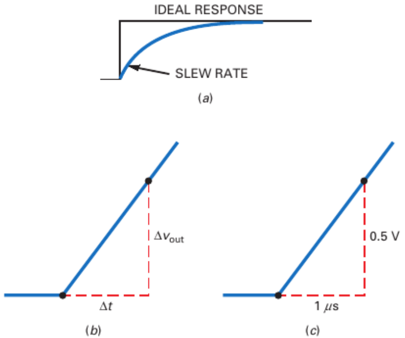
- Tidak ada input signal → input bias dan offset → error output
- Error output berkurang ← base resistor yang sama → hanya menghilangkan arus bias tapi tidak arus offset dan tegangan offset
- Solusi: menggunakan rangkaian nulling di datasheet

CMRR, MPP, dan A_{VOL}



Gambar. 8: Grafik (a) Common-Mode Rejection Ratio (CMRR), (b) Maximum Peak-to-Peak Output (MPP), dan (c) Open-Loop Voltage Gain A_{VOL} dari 741C

Slew Rate



Gambar. 9: (a) Respon ideal dan aktual terhadap tegangan step input, (b) ilustrasi definisi slew rate, (c) $S_R = 0.5$ V/μs

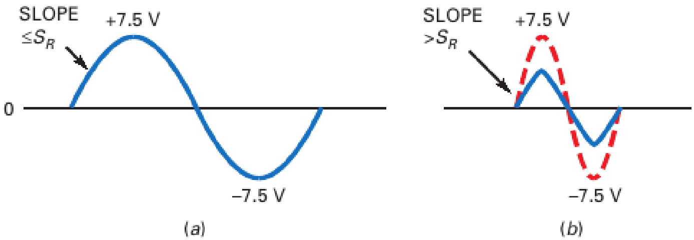
- Persamaan slew rate, S_R

$$S_R = \frac{\Delta v_{out}}{\Delta t} \tag{1}$$

- Exponential wave meningkat 0.5 V selama 1 mikrodetik pertama:

$$\begin{aligned} S_R &= \frac{\Delta v_{out}}{\Delta t} \\ &= \frac{0.5 \text{ V}}{1 \ \mu\text{s}} \\ &= 0.5 \text{ V}/\mu\text{s} \end{aligned}$$

Slew Rate



Gambar. 10: (a) Initial slope dari gelombang sinus, (b) distorsi terjadi jika initial slope melebihi slew rate

Slew Rate

- Sinyal dan frekuensinya sangat kecil $\rightarrow$ slew rate bukan masalah
- Sinyal dan frekuensinya sangat besar $\rightarrow$ slew rate akan mendistorsi sinyal ouput

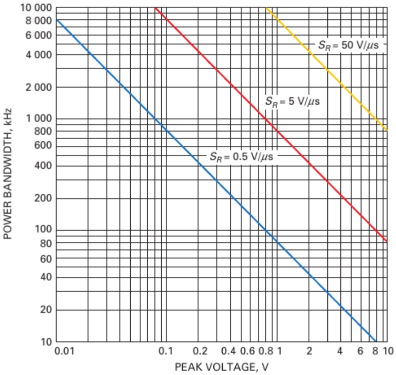
$$S_S = 2\pi f V_p$$

- S_s: initial slope dari gelombang sinus, f: frekuensi, V_p: nilai peak

$$\begin{aligned} S_S &\leq S_R \\ 2\pi f V_p &\leq S_R \\ f &\leq \frac{S_R}{2\pi V_p} \end{aligned}$$

$$f_{max} = \frac{S_R}{2\pi V_p} \tag{2}$$

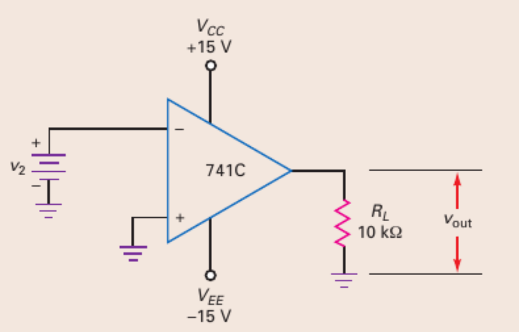
Slew Rate



Gambar. 11: Grafik power bandwidth vs. peak voltage

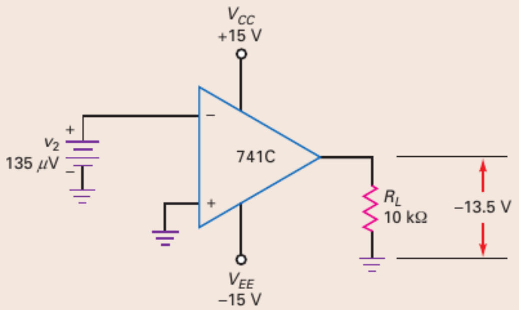
- f_{max}: power bandwidth atau large-signal bandwidth
- $S_R = 0.5\ \mathrm{V}/\mu\mathrm{s} \rightarrow$ 741C
- $S_R = 50\ \mathrm{V}/\mu\mathrm{s} \rightarrow$ LM318

Contoh Soal 2.1



- Pertanyaan:
  - Berapa tegangan inverting input yang dibutuhkan untuk men-drive op amp 741C hingga saturasi negatif?

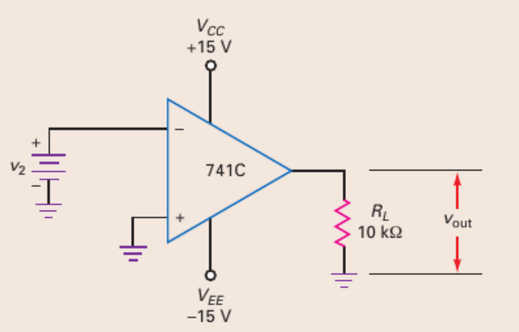
Contoh Soal 2.1



- Jawaban:
  - Berdasarkan Gambar 8 (b), MPP = 27 V untuk $R_L =$ kΩ
  - Sehingga tegangan output negatif saturasinya = - 13.5 V
  - Karena $A_{VOL} = 100000$, maka tegangan input yang dibutuhkan:

$$v_2 = \frac{v_{out}}{A_{VOL}} = \frac{13.5 \text{ V}}{100000} = 135\ \mu\text{V}$$

Latihan Soal 2.1



- Pertanyaan:
  - Berapa tegangan inverting input yang dibutuhkan untuk men-drive op amp 741C hingga saturasi negatif jika $A_{VOL} = 200000$?

Contoh Soal 2.2

- Pertanyaan:
  - Berapa common-mode rejection ratio (CMRR) dari 741C ketika frekuensi input-nya adalah 100 kHz?
- Jawaban:
  - Berdasarkan Gambar 8 (a), $\text{CMRR}_{\text{dB}} \approx 40$ dB

$$\text{CMRR} = 10^{(\text{CMRR}_{\text{dB}}/20)} = 10^{(40\ \text{dB}/20)} = 100$$

Latihan Soal 2.2

- Pertanyaan:
  - Berapa common-mode rejection ratio (CMRR) dari 741C ketika frekuensi input-nya adalah 10 kHz?

Contoh Soal 2.3

- Pertanyaan:
  - Berapa open-loop voltage gain dari 741C jika frekuensi input-nya adalah 1 kHz ? 10 kHz ? 100 kHz ?
- Jawaban:
  - Berdasarkan Gambar 8 (c), voltage gain-nya adalah 1000 untuk 1 kHz, 100 untuk 10 kHz, dan 10 untuk 100 kHz.

Contoh Soal 2.4

- Pertanyaan:
  - Tegangan input ke op amp adalah tegangan fungsi step. Output-nya adalah sebuah waveform eksponensial yang berubah ke 0.25 V dalam 0.1 μs. Berapa slew rate dari op amp tersebut?
- Jawaban:
  - Berdasarkan Persamaan 1

$$S_R = \frac{\Delta v_{out}}{\Delta t} = \frac{0.25 \text{ V}}{0.1 \ \mu\text{s}} = 2.5 \text{ V}/\mu\text{s}$$

Latihan Soal 2.4

- Pertanyaan:
  - Tegangan input ke op amp adalah tegangan fungsi step. Output-nya adalah sebuah waveform eksponensial yang berubah ke 0.8 V dalam 0.2 μs. Berapa slew rate dari op amp tersebut?

Contoh Soal 2.5

- Pertanyaan:
  - Op amp LF411A dengan slew rate 15 V/μs. Berapa power bandwidth dari tegangan peak output 10 V ?
- Jawaban:
  - Berdasarkan Persamaan 2

$$f_{max} = \frac{S_R}{2\pi V_p} = \frac{15 \text{ V}/\mu\text{s}}{2\pi(10 \text{ V})} = 239 \text{ kHz}$$

Latihan Soal 2.5

- Pertanyaan:
  - Op amp LF411A dengan slew rate 15 $V/\mu s$. Berapa power bandwidth dari tegangan peak output 200 mV ?

Contoh Soal 2.6

- Pertanyaan:
  - Berapa power bandwidth dari:
    - $S_R = 0.5$ V/μs dan $V_p = 8$ V
    - $S_R = 5$ V/μs dan $V_p = 8$ V
    - $S_R = 50$ V/μs dan $V_p = 8$ V
- Jawaban:
  - Berdasarkan Gambar 11
    - $f_{max} = 10$ kHz
    - $f_{max} = 100$ kHz
    - $f_{max} = 1$ MHz

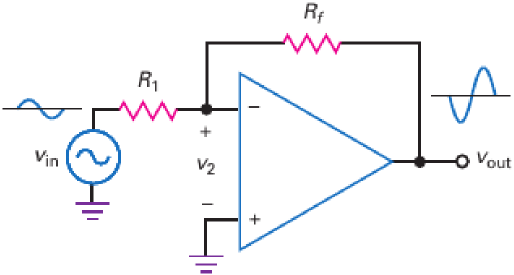
Latihan Soal 2.6

- Pertanyaan:
  - Berapa power bandwidth dari:
    - $S_R = 0.5\ \text{V}/\mu\text{s}$ dan $V_p = 1\ \text{V}$
    - $S_R = 5\ \text{V}/\mu\text{s}$ dan $V_p = 1\ \text{V}$
    - $S_R = 50\ \text{V}/\mu\text{s}$ dan $V_p = 1\ \text{V}$

Pengantar Inverting Amplifier

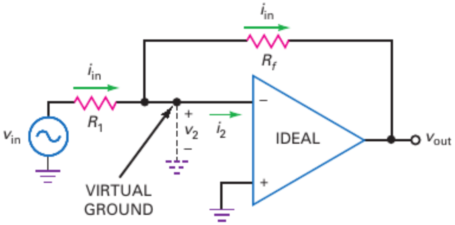
- Inverting amplifier: rangkaian op amp paling dasar
- Menggunakan negative feedback untuk menstabilkan keseluruhan voltage gain
- Keseluruhan voltage gain perlu distabilkan karena A_{VOL} sangat besar dan tidak stabil
- 741C memiliki A_{VOL} minimum sebesar 20000 dan A_{VOL} maksimum lebih dari 200000

Inverting Negative Feedback



Gambar. 12: Inverting amplifier

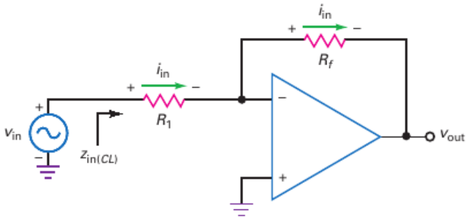
Virtual Ground



Gambar. 13: Konsep virtual ground

- Analisis inverting amplifier lebih mudah
- Berdasarkan op amp ideal:
  - $R_{in} = \infty \rightarrow i_2 = 0$
  - $A_{VOL} = \infty \rightarrow v_2 = 0 \rightarrow$
- Karena $i_2 = 0$ maka $i_{R_f} = i_{in}$

Voltage Gain & Impedansi Input



Gambar. 14: Inverting amplifier memiliki arus yang sama yang melewati kedua resistor

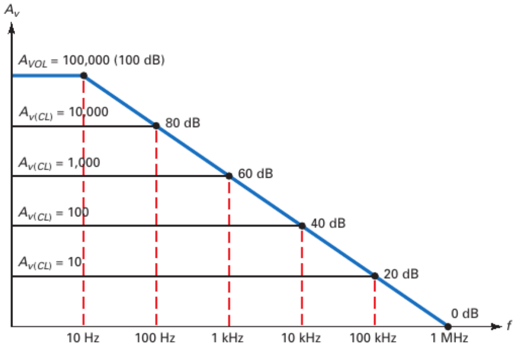
- Tegangan input: $v_{in} = i_{in}R_1$
- Tegangan output: $v_{out} = -i_{in}R_f$
- Penguatan tegangan closed-loop:

$$A_{v(CL)} = \frac{-R_f}{R_1} \tag{3}$$

- Impedansi input:

$$z_{in(CL)} = R_1 \tag{4}$$

Bandwidth



Gambar. 15: Voltage gain yang lebih kecil menghasilkan bandwidth yang lebih besar

- Closed-loop bandwidth:

$$f_{2(CL)} = \frac{f_{unity}}{A_{v(CL)}} \tag{5}$$

- Gain-band-width product (GBW):

$$f_{unity} = A_{v(CL)} f_{2(CL)} \tag{6}$$

Bias dan Offset

- Total error tegangan output:

$$V_{error} \cong \pm A_{v(CL)}(\pm V_{1err} \pm V_{2err} \pm V_{3err}) \tag{7}$$

- Error tegangan input:

$$V_{1err} = (R_{B1} - R_{(B2)})I_{in(bias)} \tag{8}$$

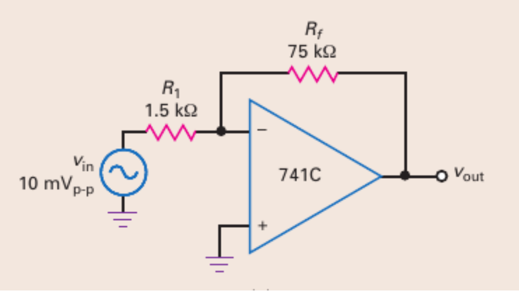
$$V_{2err} = (R_{B1} + R_{(B2)})\frac{I_{in(off)}}{2} \tag{9}$$

$$V_{3err} = V_{in(off)} \tag{10}$$

- Resistor Thevenin

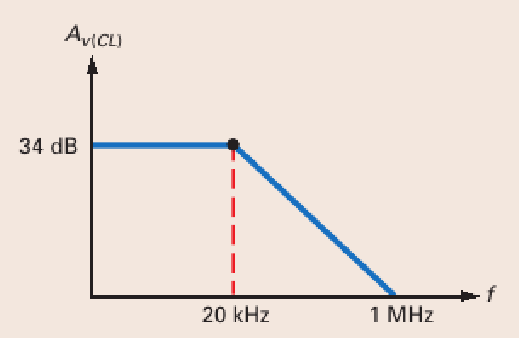
$$R_{B2} = R_1 \parallel R_f \tag{11}$$

Contoh Soal 2.7



- Pertanyaan:
  - Berapa penguatan tegangan closed-loop dan bandwidth closed-loop nya?
  - Berapa tegangan output di 1 kHz? dan di 1 MHz?

Contoh Soal 2.7



- Jawaban:
  - Penguatan tegangan closed-loop:

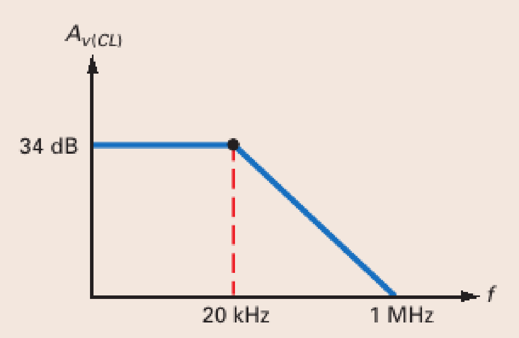
$$A_{v(CL)} = \frac{-R_f}{R_1} = \frac{-75\ \text{k}\Omega}{1.5\ \text{k}\Omega} = -50$$

  - Bandwidth closed-loop:

$$f_{2(CL)} = \frac{f_{unity}}{A_{v(CL)}} = \frac{1\ \text{MHz}}{50} = 20\ \text{kHz}$$

  - Ideal bode-plot dari $A_{v(CL)}$

Contoh Soal 2.7



- Jawaban:
  - Tegangan output di 1 kHz:

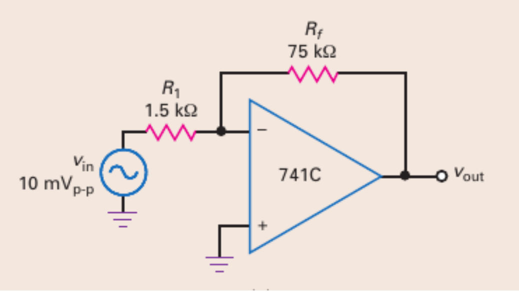
$$v_{out} = (A_{v(CL)})(v_{in}) = (-50)(10 \text{ mVp-p})$$
$$= -500 \text{ mVp-p}$$

  - Tegangan output di 1 MHz. Karena 1 MHz adalah unity-gain frekuensinya, maka

$$v_{out} = -10 \text{ mVp-p}$$

  - Tanda negatif menunjukkan phase-shift 180° antara input dan output

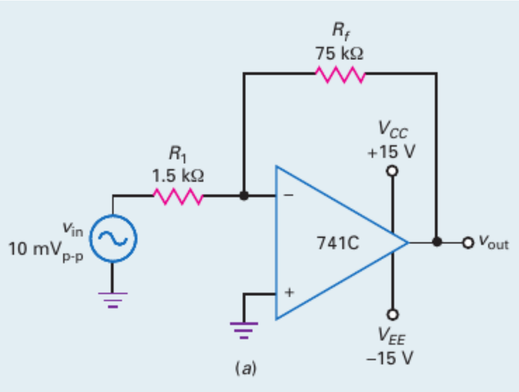
Latihan Soal 2.7



- Pertanyaan:
  - Berapa tegangan output di 100 kHz ?
  - *Hint:* Gunakan persamaan

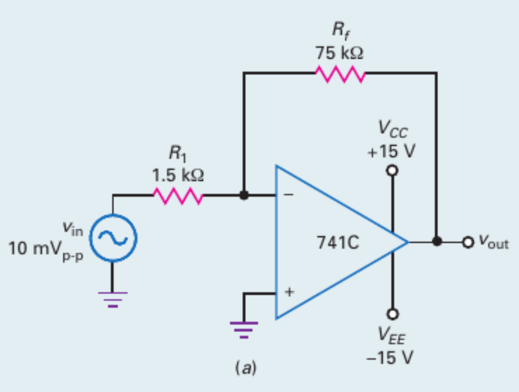
$$A_v = \frac{A_{v(mid)}}{\sqrt{1 + (f/f_2)^2}}$$

Contoh Soal 2.8



- Pertanyaan:
  - Berapa tegangan output ketika $v_{in} = 0$?

Contoh Soal 2.8



- Jawaban:
  - Berdasarkan Tabel di Gambar 3, didapatkan:

$$I_{in(bias)} = 80 \text{ nA}$$

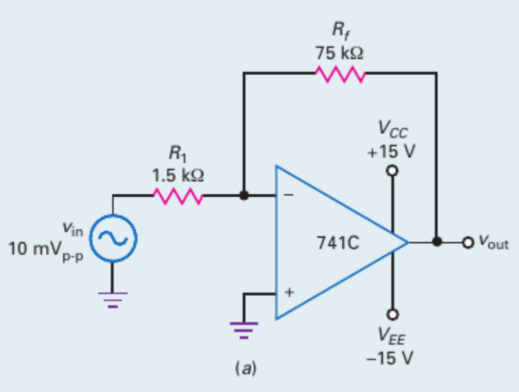
$$I_{in(off)} = 20 \text{ nA}$$

$$V_{in(off)} = 2 \text{ mV}$$

  - Berdasarkan Persamaan 11:

$$\begin{aligned} R_{B2} &= R_1 \parallel R_f = 1.5 \text{ k}\Omega \parallel 75 \text{ k}\Omega \\ &= 1.47 \text{ k}\Omega \end{aligned}$$

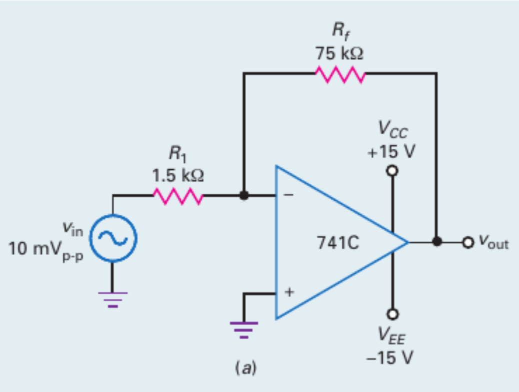
Contoh Soal 2.8



- Jawaban:
  - Error tegangan input:

$$
\begin{aligned}
V_{1err} &= (R_{B1} - R_{B2}) I_{in(bias)} \\
&= (-1.47\ \mathrm{k\Omega})(80\ \mathrm{nA}) \\
&= -0.118\ \mathrm{mV} \\
V_{2err} &= (R_{B1} + R_{B2}) \frac{I_{in(off)}}{2} \\
&= (1.47\ \mathrm{k\Omega})(10\ \mathrm{nA}) \\
&= 0.0147\ \mathrm{mV} \\
V_{3err} &= V_{in(off)} = 2\ \mathrm{mV}
\end{aligned}
$$

Contoh Soal 2.8



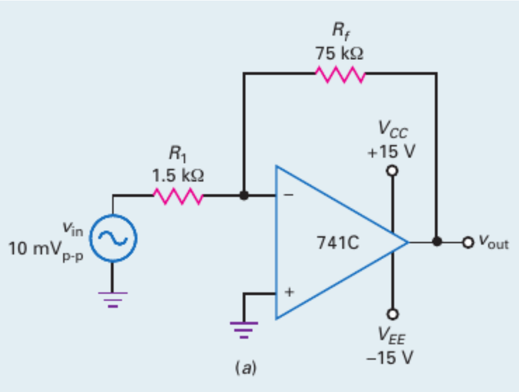
- Jawaban:
  - Penguatan tegangan closed-loop:

$$A_{v(CL)} = \frac{-R_f}{R_1} = \frac{-75\ \text{k}\Omega}{1.5\ \text{k}\Omega} = -50$$

  - Error tegangan output:

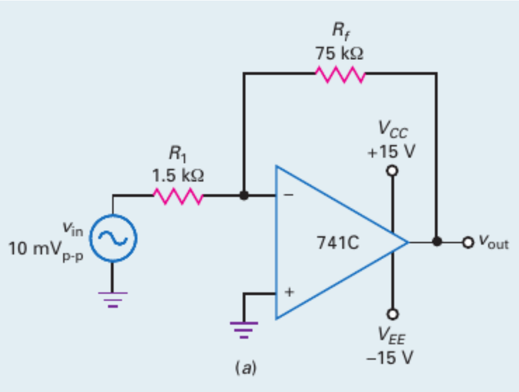
$$\begin{aligned} V_{error} &= \pm 50(V_{1err} + V_{2err} + V_{2err}) \\ &= \pm 50(0.118\text{mV} + 0.0147\text{mV} + 2\text{mV}) \\ &= \pm 107\ \text{mV} \end{aligned}$$

Latihan Soal 2.8



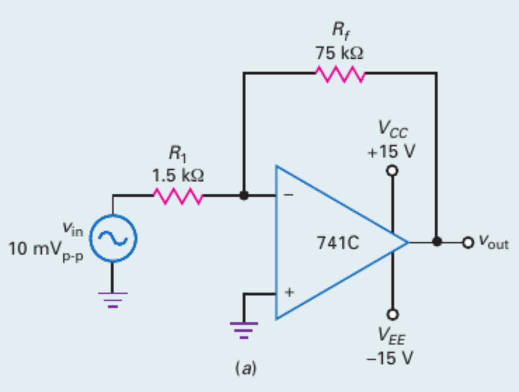
- Pertanyaan:
  - Jika op amp yang digunakan adalah LF157A, berapa tegangan output ketika $v_{in} = 0$?

Contoh Soal 2.9



- Pertanyaan:
  - Diketahui:
    $I_{in(bias)} = 500$ nA,
    $I_{in(off)} = 200$ nA, dan
    $V_{in(off)} = 6$ mV
  - Berapa tegangan output jika $v_{in} = 0$?

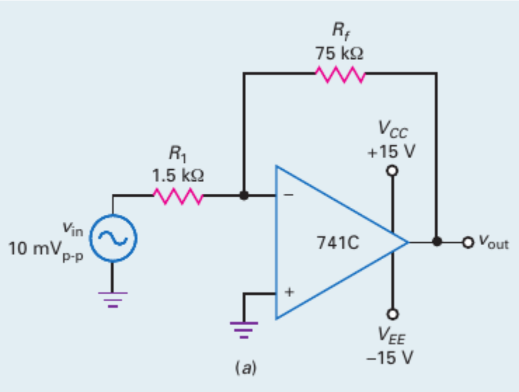
Contoh Soal 2.9



- Jawaban:
  - Error tegangan input:

$$
\begin{aligned}
V_{1err} &= (R_{B1} - R_{B2}) I_{in(bias)} \\
&= (-1.47\ \text{k}\Omega)(500\ \text{nA}) \\
&= -0.735\ \text{mV} \\
V_{2err} &= (R_{B1} + R_{B2}) \frac{I_{in(off)}}{2} \\
&= (1.47\ \text{k}\Omega)(100\ \text{nA}) \\
&= 0.147\ \text{mV} \\
V_{3err} &= V_{in(off)} = 6\ \text{mV}
\end{aligned}
$$

Contoh Soal 2.9



- Jawaban:
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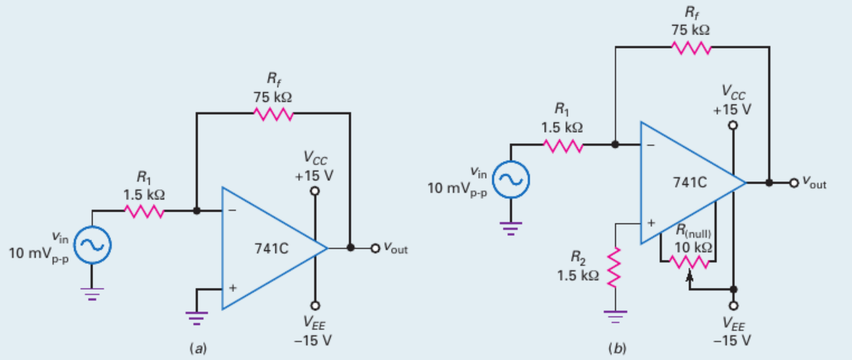
$$A_{v(CL)} = \frac{-R_f}{R_1} = \frac{-75\ \text{k}\Omega}{1.5\ \text{k}\Omega} = -50$$

  - Error tegangan output:

$$\begin{aligned} V_{error} &= \pm 50(V_{1err} + V_{2err} + V_{2err}) \\ &= \pm 50(0.735\text{mV} + 0.147\text{mV} + 6\text{mV}) \\ &= \pm 344\ \text{mV} \end{aligned}$$

Contoh Soal 2.9

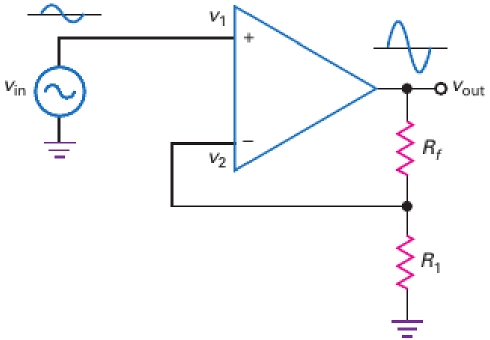


Gambar. 16: (a) Rangkaian op amp 741C dan (b) Rangkaian op amp 741C dengan penambahan compensating resistor dan potensiometer

Pengantar Non-inverting Amplifier

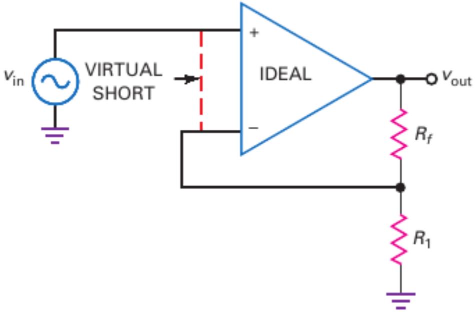
- Salah satu rangkaian op amp dasar
- Menggunakan negative feedback untuk menstabilkan overall voltage gain
- Negative feedback juga meningkatkan impedansi input dan menurunkan impedansi output

Rangkaian Dasar



Gambar. 17: Non-inverting amplifier

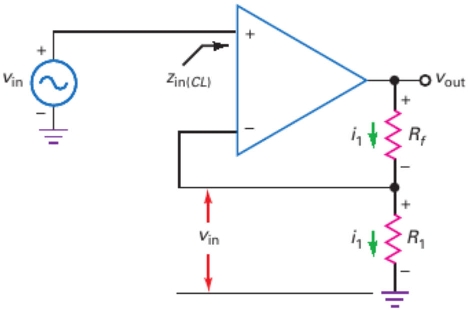
Virtual Short



Gambar. 18: Virtual short

- Virtual short digunakan untuk menganalisis noninverting amplifier
- Virtual short berdasarkan 2 sifat dari op amp ideal
  1. $R_{in} = \infty \rightarrow i_1 = i_2 = 0$
  2. $A_{VOL} = \infty \rightarrow v_1 - v_2 = 0$

Voltage Gain



Gambar. 19: Tegangan input ada di R_1 dan arus yang sama mengalir di R_1

- Tegangan input: $v_{in} = i_1 R_1$
- Tegangan output: $v_{out} = i_1(R_f + R_1)$
- Penguatan tegangan closed-loop:

$$A_{v(CL)} = \frac{v_{out}}{v_{in}} = \frac{i_1(R_f + R_1)}{i_1 R_1} = \frac{R_f + R_1}{R_1}$$

maka

$$A_{v(CL)} = \frac{R_f}{R_1} + 1 \qquad (12)$$

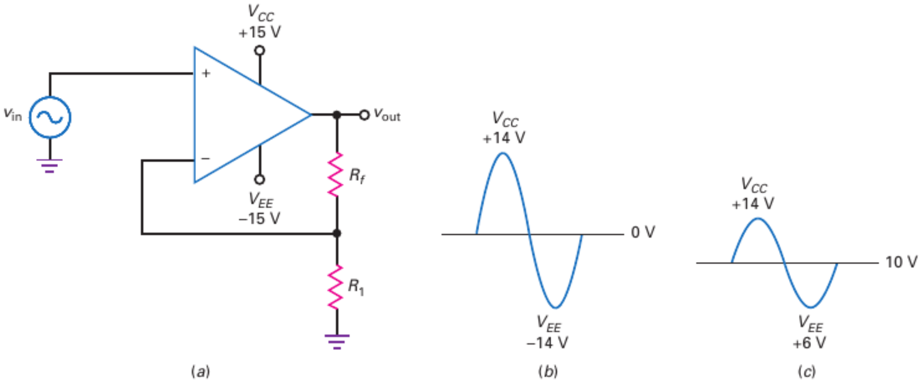
Impedansi Input, Bandwidth, Bias & Offset

- Karena impedansi input open-loop sudah sangat besar (2 MΩ untuk 741C), maka impedansi input closed-loop lebih besar lagi.
- Efek negative feedback terhadap bandwidth sama seperti di inverting amplifier

$$f_{2(CL)} = \frac{f_{unity}}{A_{v(CL)}}$$

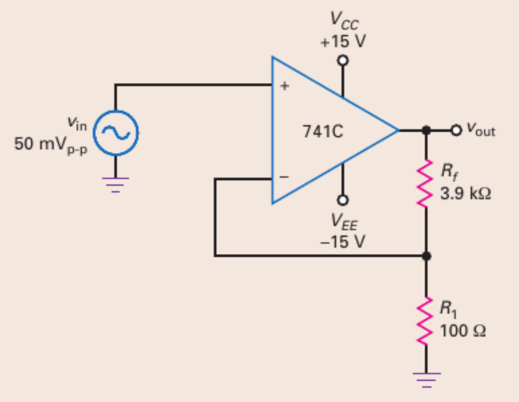
- Efek bias dan offset juga sama seperti di inverting amplifier

Error Tegangan Output Mereduksi MPP



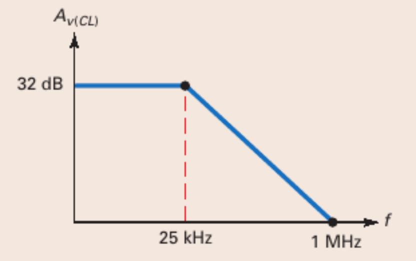
Gambar. 20: Error tegangan output dapat mereduksi MPP

Contoh Soal 2.10



- Pertanyaan:
  - Berapa penguatan tegangan closed-loop dan bandwidth?
  - Berapa tegangan output di 250 kHz?

Contoh Soal 2.10



- Jawaban:
  - Penguatan tegangan closed-loop:

$$A_{v(CL)} = \frac{R_f}{R_1} + 1 = \frac{3.9\ \text{k}\Omega}{100\ \text{k}\Omega} + 1 = 40$$

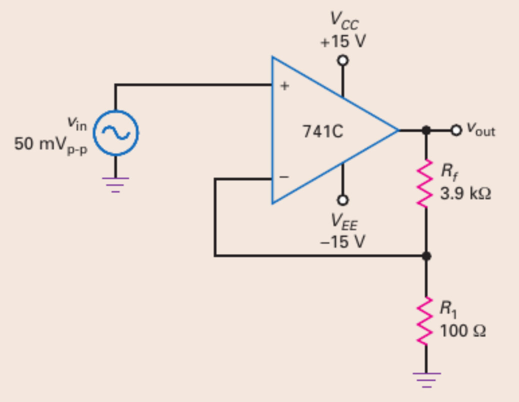
  - Bandwidth:

$$f_{2(CL)} = \frac{f_{unity}}{A_{v(CL)}} = \frac{1\ \text{MHz}}{40} = 25\ \text{kHz}$$

  - Tegangan output di 250 kHz

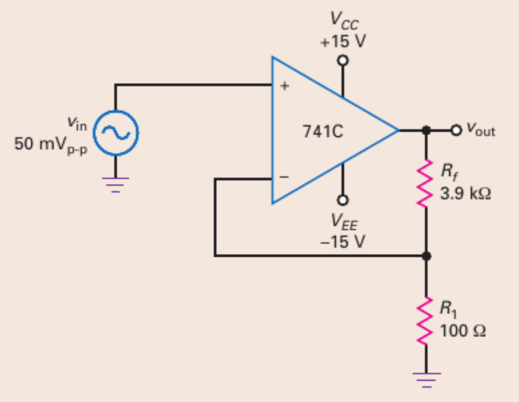
$$\begin{aligned} v_{out} &= A_{c(CL)} v_{in} = 4(50\ \text{mVp-p}) \\ &= 200\ \text{mVp-p} \end{aligned}$$

Latihan Soal 2.10



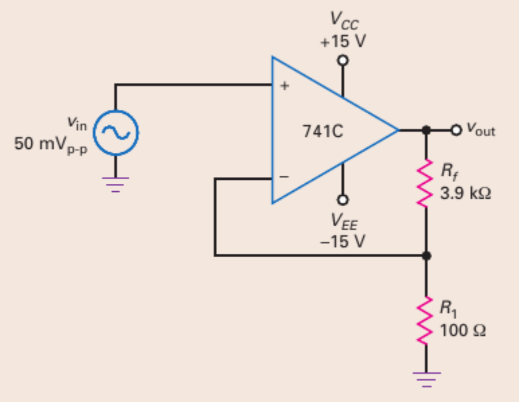
- Pertanyaan:
  - Jika $R_f = 4.9\ \text{k}\Omega$, tentukan $A_{v(CL)}$ dan v_{out} di 200 kHz.

Contoh Soal 2.11



- Pertanyaan:
  - Jika $I_{in(bias)} = 500$ nA, $I_{in(off)} = 200$ nA, dan $V_{in(off)} = 6$ mV, berapa error tegangan output?

Contoh Soal 2.11



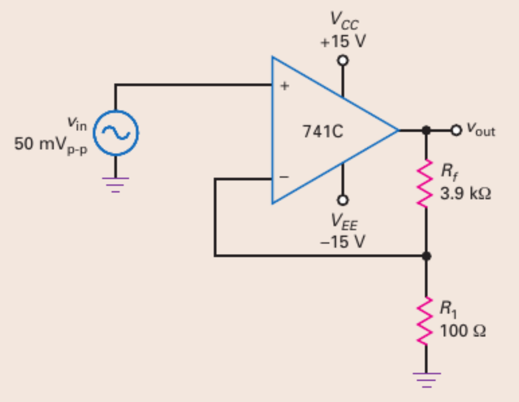
- Jawaban:
  - Resistor Thevenin:

$$R_{B2} = R_1 \parallel R_f = 3.9 \text{ k}\Omega \parallel 100 \ \Omega$$
$$R_{B2} \approx 100 \ \Omega$$

  - Error tegangan input

$$\begin{aligned} V_{1err} &= (R_{B1} - R_{B2}) I_{in(bias)} \\ &= (-100 \ \Omega)(500 \text{ nA}) = -0.05 \text{ mV} \\ V_{2err} &= (R_{B1} + R_{B2}) I_{in(bias)} \\ &= (100 \ \Omega)(100 \text{ nA}) = 0.01 \text{ mV} \\ V_{3err} &= V_{in(off)} = 6 \text{ mV} \end{aligned}$$

Contoh Soal 2.11



- Jawaban:
  - Error tegangan output

$$\begin{aligned} V_{error} &= \pm A_{v(CL)}(\pm V_{1err} \pm V_{2err} \pm V_{3err}) \\ &= \pm 40(0.05 \text{ mV} + 0.01 \text{ mV} + 6 \text{ mV}) \\ &= \pm 242 \text{ mV} \end{aligned}$$

Aplikasi Op-Amp

- Item

TERIMA KASIH