RANGKAIAN ELEKTRONIKA II

Penguat Operasional

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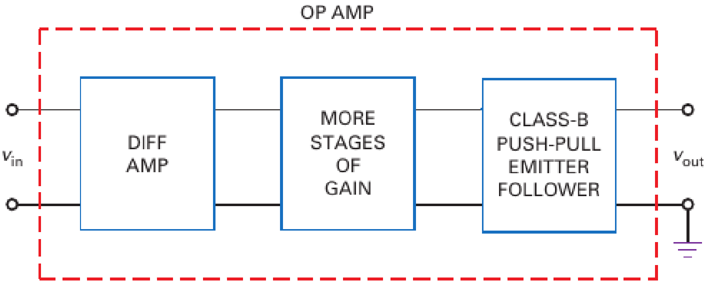
Sub-CPMK

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

Bahan Kajian

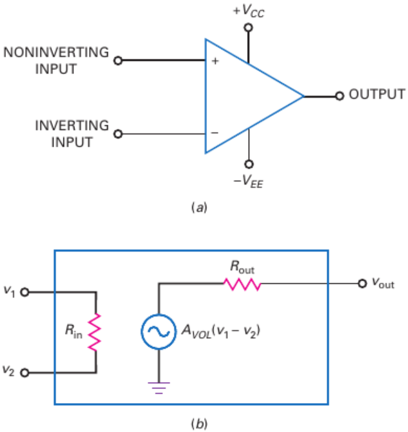
1. Konsep dasar penguat operasional;
2. Inverting amplifier;
3. Noninverting amplifier;
4. The Summing Amplifier;
5. Voltage Follower.

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

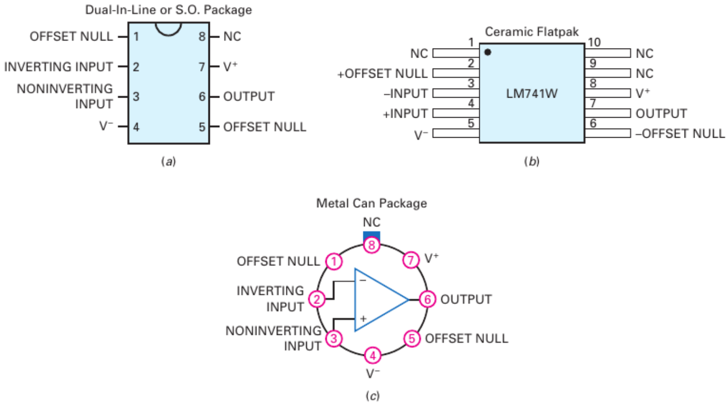
Op Amp 741

- 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

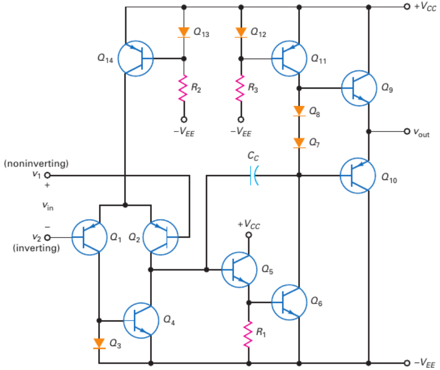
- Beberapa versi: 741, 741A, 741C, 741E, dan 741N
- Bergantung pada karakteristiknya (voltage gain, temp. range, noise level, dll)
- 741C (C = *Commercial grade*) $\rightarrow$ sedikit lebih murah dan paling banyak digunakan
- $A_{VOL} = 100000$, $z_{in} = 2\ \mathrm{M}\Omega$, $z_o ut = 75\ \Omega$

Standar Industri



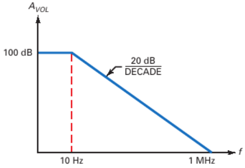
Gambar. 4: Op amp 741 pinouts (a) dual-in-line, (b) ceramic flatpak, (c) metal can

Rangkaian Ekivalen dari Op Amp 741



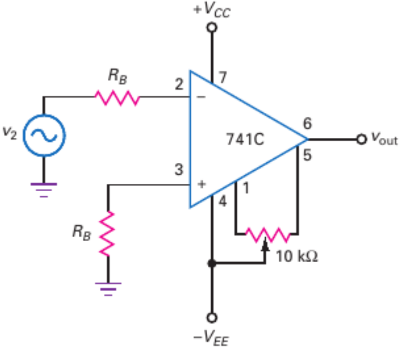
Gambar. 5: Rangkaian ekivalen dari op amp 741

- 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

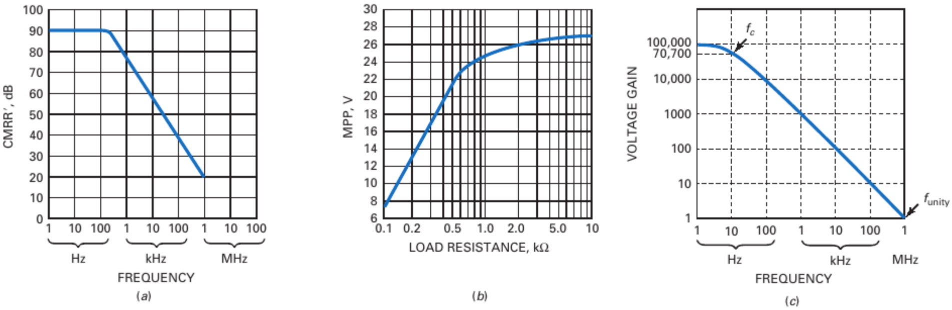
Bias & Offset



Gambar. 7: Penggunaan compensation dan nulling 741C

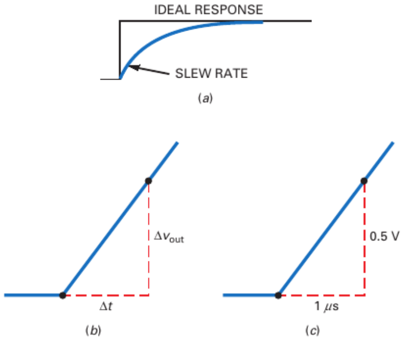
- Tidak ada input signal $\rightarrow$ input bias dan offset $\rightarrow$ error output
- Error output berkurang $\leftarrow$ base resistor yang sama $\rightarrow$ hanya menghilangkan arus bias tapi tidak arus offset dan tegangan offset
- Solusi: menggunakan rangkaian nulling di datasheet

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$/\mu$s

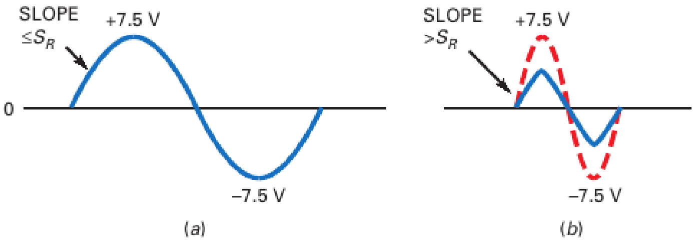
- Persamaan slew rate, S_R

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

- 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

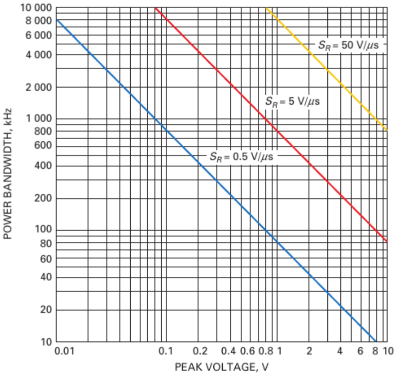
$$S_S = 2\pi f V_p$$

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

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

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

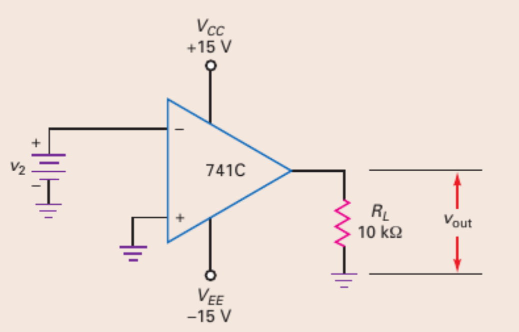
Slew Rate



Gambar. 11: Grafik power bandwidth vs. peak voltage

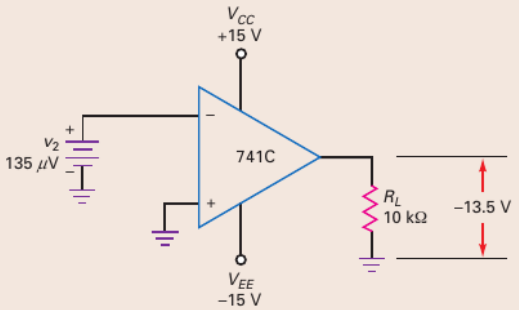
- f_{max}: power bandwidth atau large-signal bandwidth
- $S_R = 0.5\ V/\mu s \rightarrow 741C$
- $S_R = 50\ V/\mu s \rightarrow LM318$

Contoh Soal 2.1



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

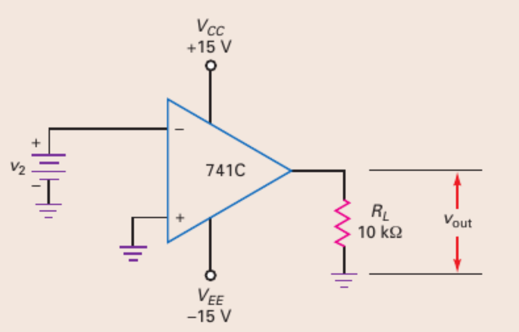
Contoh Soal 2.1



- 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), $\mathrm{CMRR_{dB}} \approx 40$ dB

$$\mathrm{CMRR} = 10^{(\mathrm{CMRR_{dB}}/20)} = 10^{(40\ \mathrm{dB}/20)} = 100$$

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

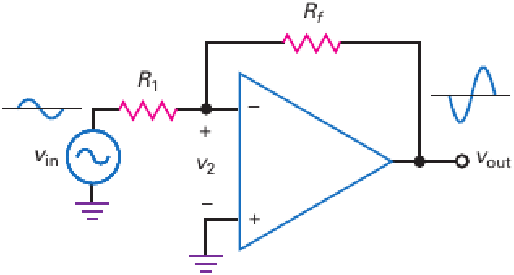
Latihan Soal 2.6

- Pertanyaan:
  - Berapa power bandwidth dari:
    - $S_R = 0.5$ V/μs dan $V_p = 1$ V
    - $S_R = 5$ V/μs dan $V_p = 1$ V
    - $S_R = 50$ V/μs dan $V_p = 1$ V

Pengantar Inverting Amplifier

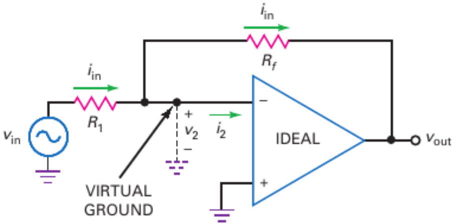
- Inverting amplifier: rangkaian op amp paling dasar
- Menggunakan negative feedback untuk menstabilkan keseluruhan voltage gain
- Keseluruhan voltage gain perlu distabilkan karena A_{VOL} sangat besar dan tidak stabil
- 741C memiliki A_{VOL} minimum sebesar 20000 dan A_{VOL} maksimum lebih dari 200000

Inverting Negative Feedback



Gambar. 12: Inverting amplifier

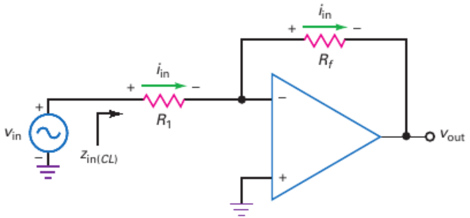
Virtual Ground



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

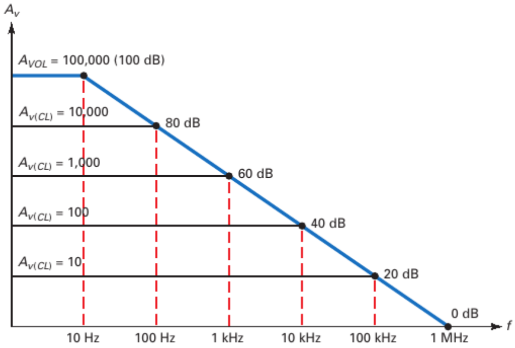
- Tegangan input: $v_{in} = i_{in}R_1$
- Tegangan output: $v_{out} = -i_{in}R_f$
- Penguatan tegangan closed-loop:

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

- Impedansi input:

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

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:

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

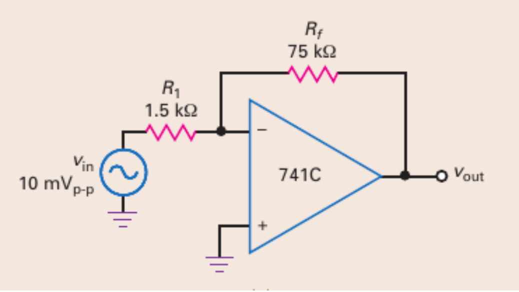
$$V_{2err} = (R_{B1} + R_{(B2)})\frac{I_{in(off)}}{2} \tag{9}$$

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

- Resistor Thevenin

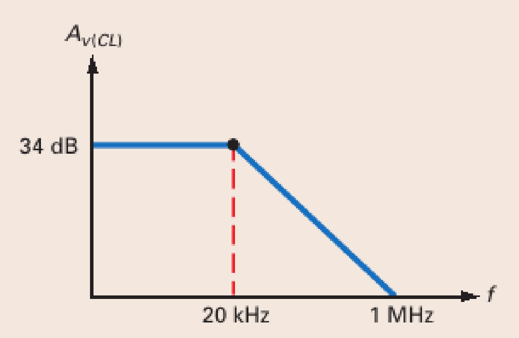
$$R_{B2} = R_1 \parallel R_f \tag{11}$$

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:

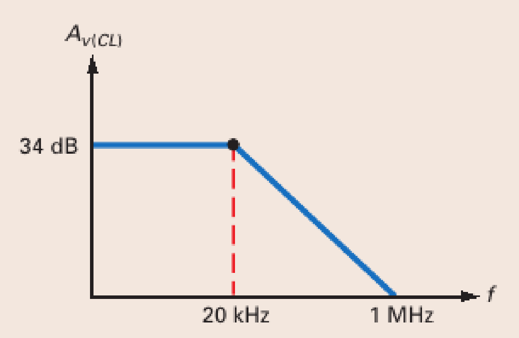
$$A_{v(CL)} = \frac{-R_f}{R_1} = \frac{-75\ \text{k}\Omega}{1.5\ \text{k}\Omega} = -50$$

  - 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:

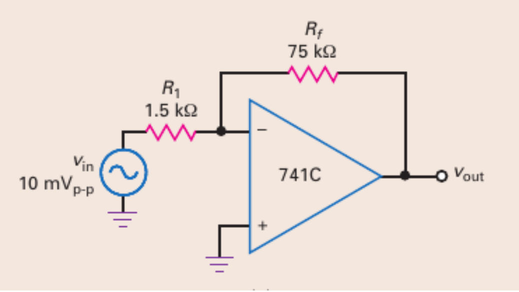
$$
\begin{aligned}
v_{out} &= (A_{v(CL)})(v_{in}) = (-50)(10 \text{ mVp-p}) \\
&= -500 \text{ mVp-p}
\end{aligned}
$$

  - 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

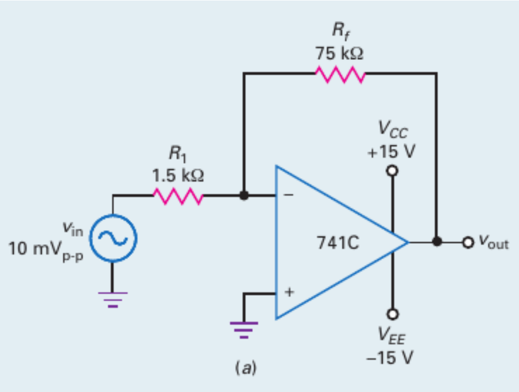
Latihan Soal 2.7



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

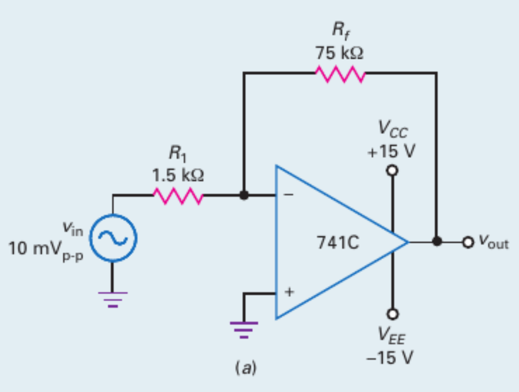
$$A_v = \frac{A_{v(mid)}}{\sqrt{1 + (f/f_2)^2}}$$

Contoh Soal 2.8



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

Contoh Soal 2.8



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

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

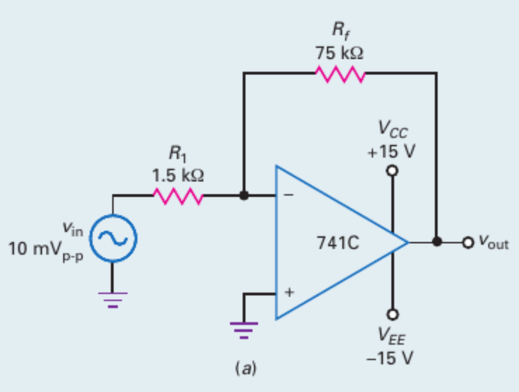
$$I_{in(off)} = 20 \text{ nA}$$

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

  - Berdasarkan Persamaan 11:

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

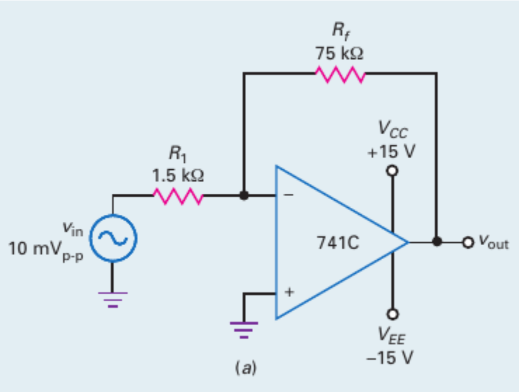
Contoh Soal 2.8



- Jawaban:
  - Error tegangan input:

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

Contoh Soal 2.8



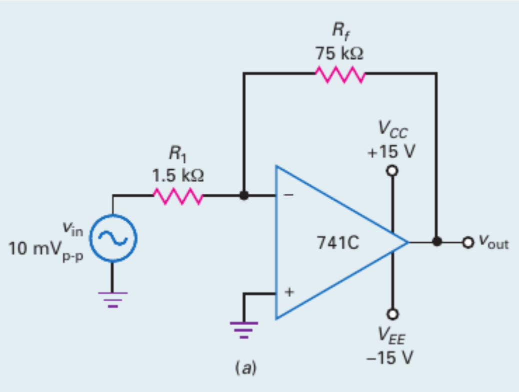
- Jawaban:
  - Penguatan tegangan closed-loop:

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

  - Error tegangan output:

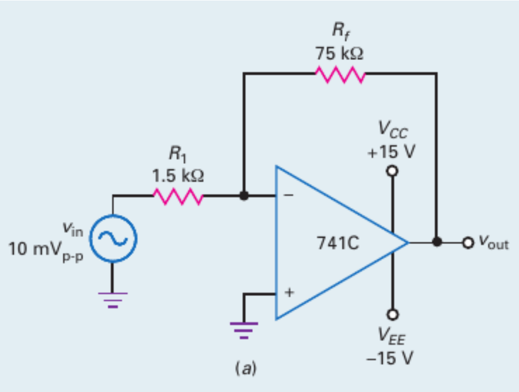
$$\begin{aligned} V_{error} &= \pm 50(V_{1err} + V_{2err} + V_{2err}) \\ &= \pm 50(0.118\text{mV} + 0.0147\text{mV} + 2\text{mV}) \\ &= \pm 107\ \text{mV} \end{aligned}$$

Latihan Soal 2.8



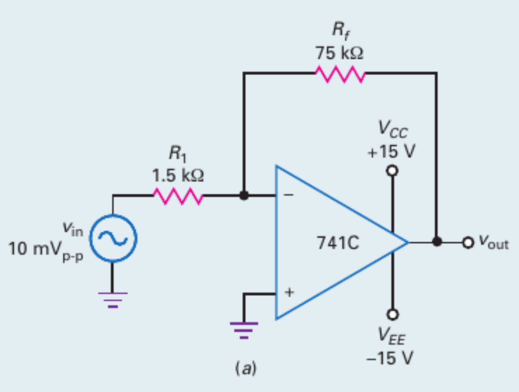
- Pertanyaan:
  - Jika op amp yang digunakan adalah LF157A, berapa tegangan output ketika $v_{in} = 0$?

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 $v_{in} = 0$?

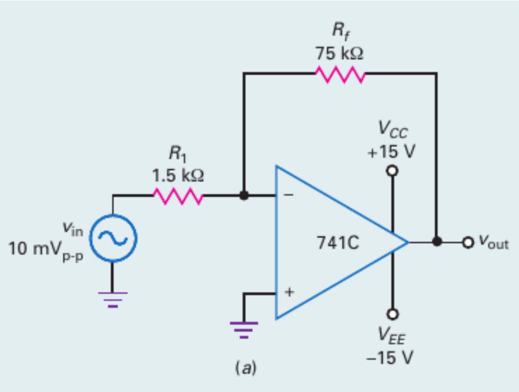
Contoh Soal 2.9



- 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



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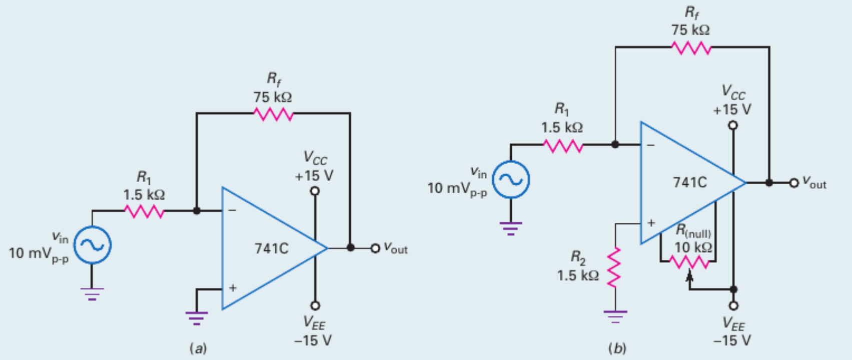
$$A_{v(CL)} = \frac{-R_f}{R_1} = \frac{-75\ \text{k}\Omega}{1.5\ \text{k}\Omega} = -50$$

  - 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

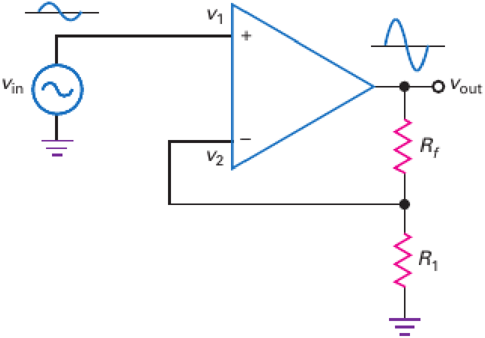


Gambar. 16: (a) Rangkaian op amp 741C dan (b) Rangkaian op amp 741C dengan penambahan compensating resistor dan potensiometer

Pengantar Non-inverting Amplifier

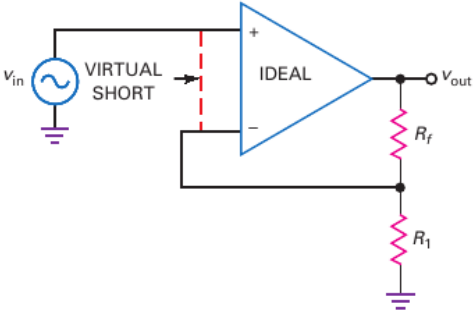
- Salah satu rangkaian op amp dasar
- Menggunakan negative feedback untuk menstabilkan overall voltage gain
- Negative feedback juga meningkatkan impedansi input dan menurunkan impedansi output

Rangkaian Dasar



Gambar. 17: Non-inverting amplifier

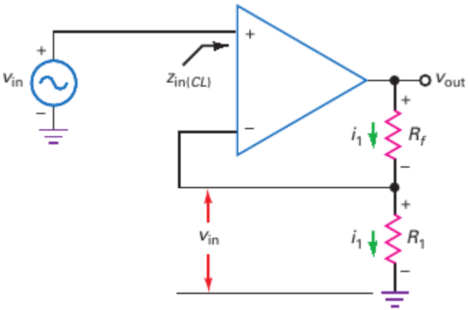
Virtual Short



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

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

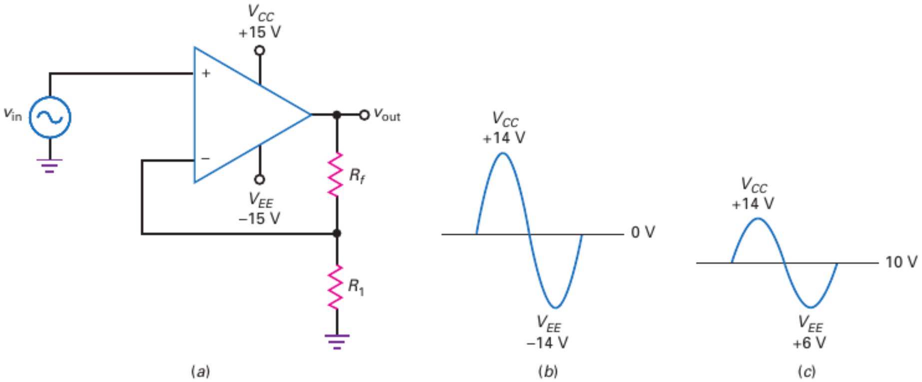
Impedansi Input, Bandwidth, Bias & Offset

- 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

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

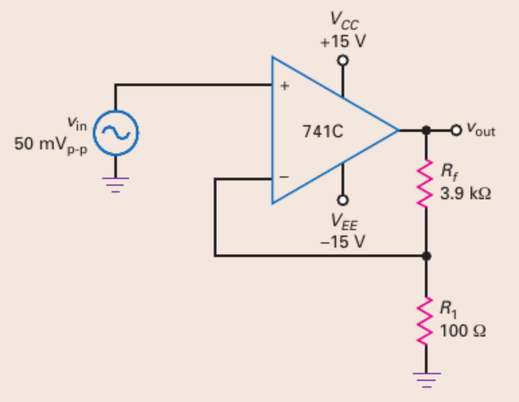
- Efek bias dan offset juga sama seperti di inverting amplifier

Error Tegangan Output Mereduksi MPP



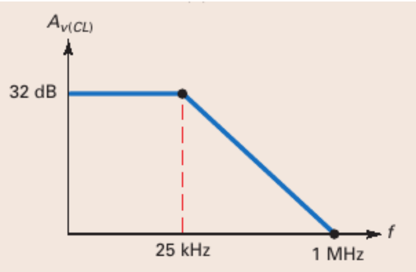
Gambar. 20: Error tegangan output dapat mereduksi MPP

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:

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

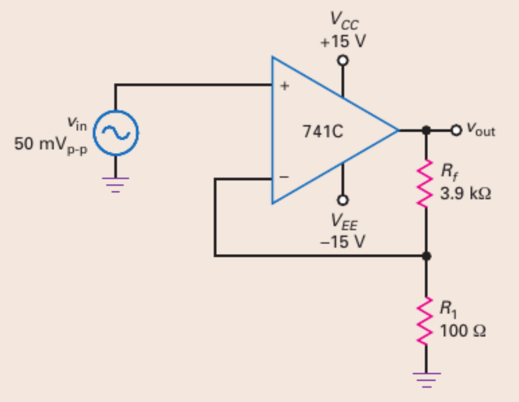
  - Bandwidth:

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

  - Tegangan output di 250 kHz

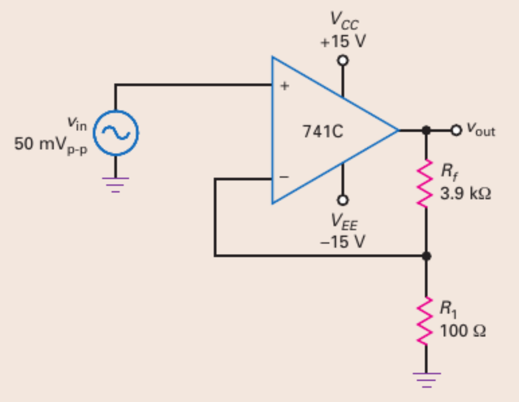
$$\begin{aligned} v_{out} &= A_{c(CL)} v_{in} = 4(50\ \text{mVp-p}) \\ &= 200\ \text{mVp-p} \end{aligned}$$

Latihan Soal 2.10



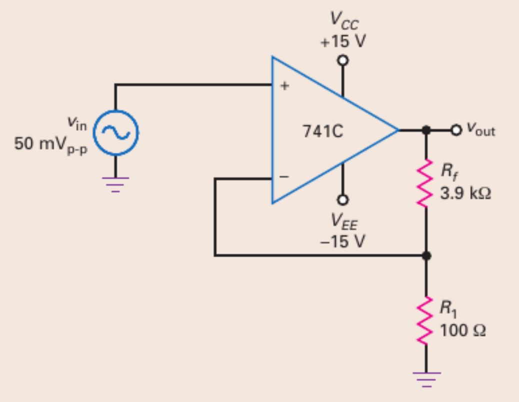
- Pertanyaan:
  - Jika $R_f = 4.9$ kΩ, tentukan $A_{v(CL)}$ dan v_{out} di 200 kHz.

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



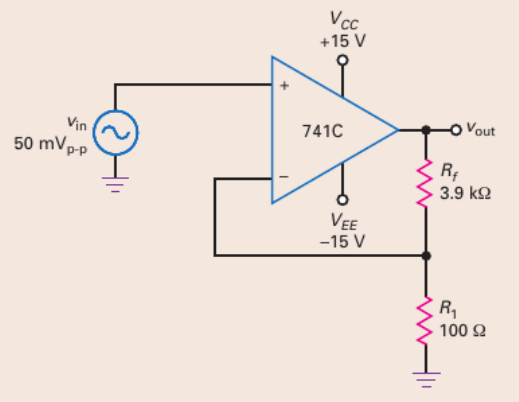
- Jawaban:
  - Resistor Thevenin:

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

  - 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



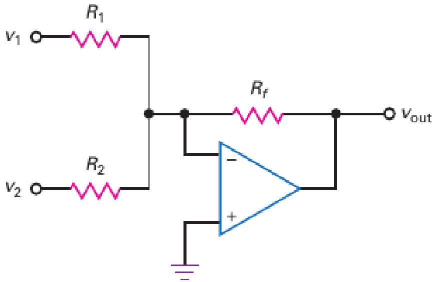
- Jawaban:
  - Error tegangan output

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

Pengantar Aplikasi Op-Amp

- Aplikasi dari op amp sangat luas sekali dan beraneka ragam
- Tidak mungkin menjelaskannya secara komprehensif
- Sementara kita fokus pada 2 rangkaian dulu.

The Summing Amplifier



Gambar. 21: Rangkaian umming amplifier

- Menggabungkan 2 atau lebih sinyal analog menjadi satu output
- Menguatkan setiap sinyal input
- Penguatan setiap channel atau input

$$A_{v1(CL)} = \frac{-R_f}{R_1}; \quad A_{v2(CL)} = \frac{-R_f}{R_2}$$

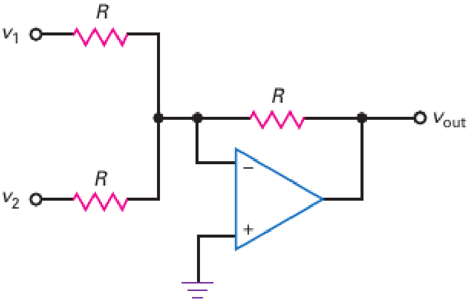
- Tegangan output

$$v_{out} = A_{v1(CL)} v_1 + A_{v2(CL)} v_2 \tag{13}$$

- Resistor Thevenin:

$$R_{B2} = R_1 \parallel R_2 \parallel R_f \parallel \cdots \parallel R_n \tag{14}$$

The Summing Amplifier

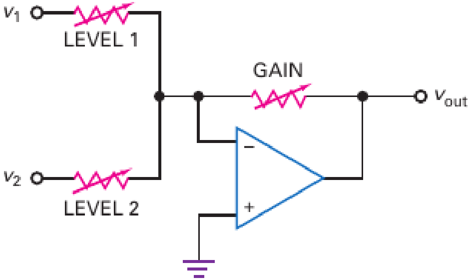


Gambar. 22: Rangkaian summing amplifier dengan resistor yang sama

- Tegangan output

$$v_{out} = -(v_1 + v_2 + \cdots + v_n)$$

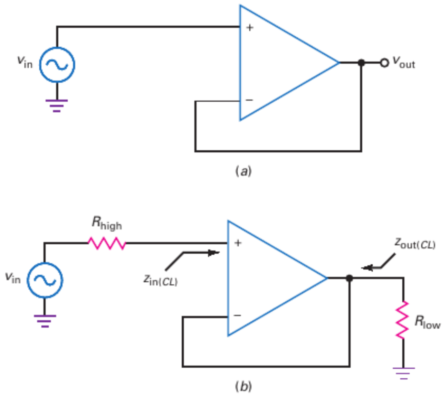
The Summing Amplifier



Gambar. 23: Rangkaian mixer

- Menggabungkan sinyal audio
- Menurunkan LEVEL 1 $\rightarrow$ sinyal v_1 semakin nyaring di output
- Menurunkan LEVEL 2 $\rightarrow$ sinyal v_2 semakin nyaring di output
- Meningkatkan GAIN $\rightarrow$ kedua sinyal semakin nyaring

Voltage Follower



Gambar. 24: Rangkaian voltage follower

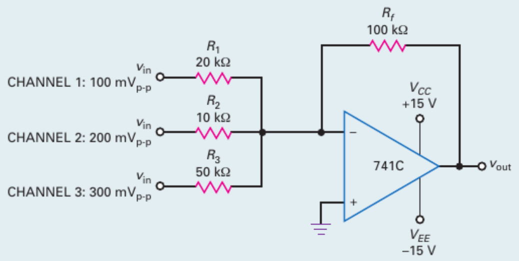
- Penguatan tegangan closed-loop:

$$A_{v(CL)} = 1 \tag{15}$$

- Bandwidth closed-loop:

$$f_{2(CL)} = f_{unity} \tag{16}$$

Contoh Soal 2.12



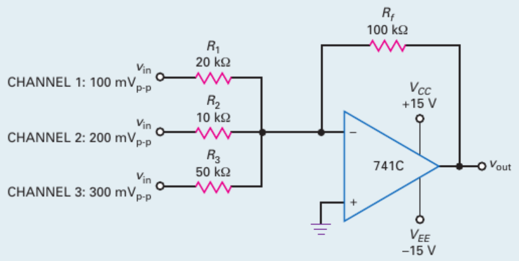
- Pertanyaan:
  - Berapa tegangan output ac?
- Jawaban:
  - Penguatan tegangan tiap channel:

$$A_{v1(CL)} = \frac{-R_f}{R_1} = \frac{-100\ \text{k}\Omega}{20\ \text{k}\Omega} = -5$$

$$A_{v2(CL)} = \frac{-R_f}{R_2} = \frac{-100\ \text{k}\Omega}{10\ \text{k}\Omega} = -10$$

$$A_{v3(CL)} = \frac{-R_f}{R_3} = \frac{-100\ \text{k}\Omega}{50\ \text{k}\Omega} = -2$$

Contoh Soal 2.12



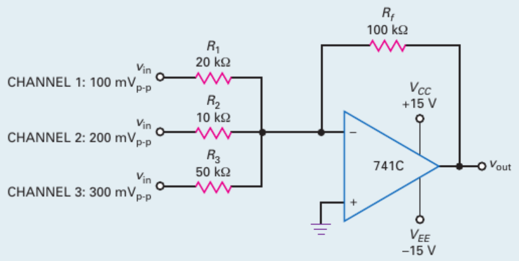
- Jawaban:
  - Tegangan output:

$$v_{out} = A_{v1(CL)} v_1 + A_{v2(CL)} v_2 + A_{v3(CL)} v_3$$

  - Jika diperlukan untuk mengkompensasi bias input dengan menambahkan R_B yang sama ke noninverting input

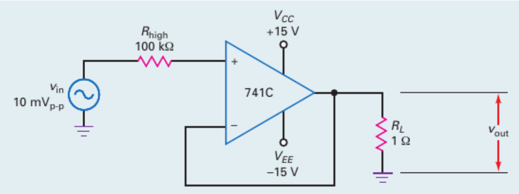
$$\begin{aligned} R_{B2} &= R_1 \parallel R_2 \parallel R_3 \parallel R_f \\ &= 20\ \text{k}\Omega \parallel 10\ \text{k}\Omega \parallel 50\ \text{k}\Omega \parallel 100\ \text{k}\Omega \\ &= 5.56\ \text{k}\Omega \end{aligned}$$

Latihan Soal 2.12



- Pertanyaan:
  - Jika tegangan input peak-to-peak diganti dengan tegangan positif dc, berapakah tegangan output dc-nya?

Contoh Soal 2.13



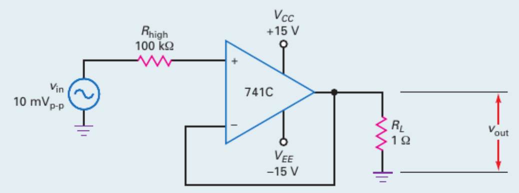
- Pertanyaan:
  - Berapa tegangan output dan bandwidth?
- Jawaban:
  - Penguatan tegangan closed-loopnya adalah unity, sehingga:

$$v_{out} = A_{v(CL)} v_{in} = 1(10\ \text{mV}_{\text{p-p}})$$

  - Bandwidthnya adalah:

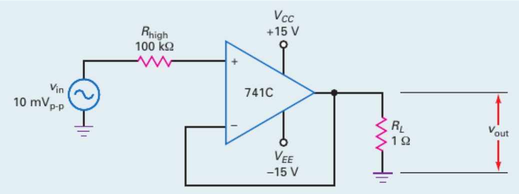
$$f_{2(CL)} = f_{unity} = 1\ \text{MHz}$$

Latihan Soal 2.13



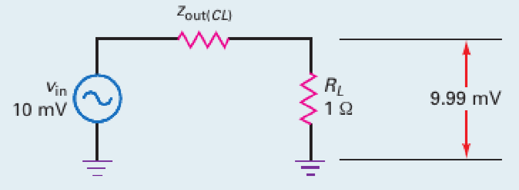
- Pertanyaan:
  - Berapa tegangan output dan bandwidth jika op amp yang digunakan adalah LF157A?

Contoh Soal 2.14



- Pertanyaan:
  - Jika rangkaian voltage follower di samping dibuat dengan Multisim, tegangan output di 1 Ω adalah 9.99 mV. Tentukan berapa impedansi output closed-loop?

Contoh Soal 2.14



- Jawaban:
  - Tegangan output:

$$v_{out} = 9.99 \text{ mV}$$

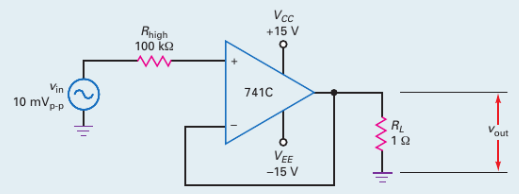
  - Arus di beban adalah:

$$i_{out} = \frac{9.99 \text{ mV}}{1\ \Omega} = 9.99 \text{ mA}$$

  - Impedansi output closed-loop

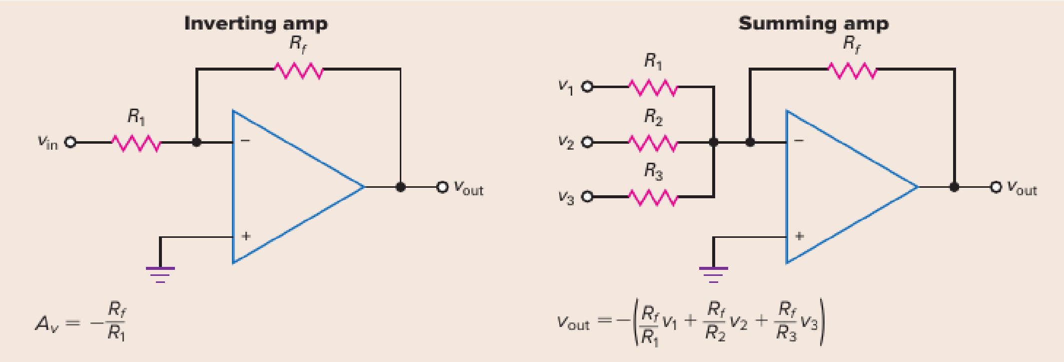
$$z_{out(CL)} = \frac{0.01 \text{ mV}}{9.99 \text{ mA}} = 0.001\ \Omega$$

Latihan Soal 2.14



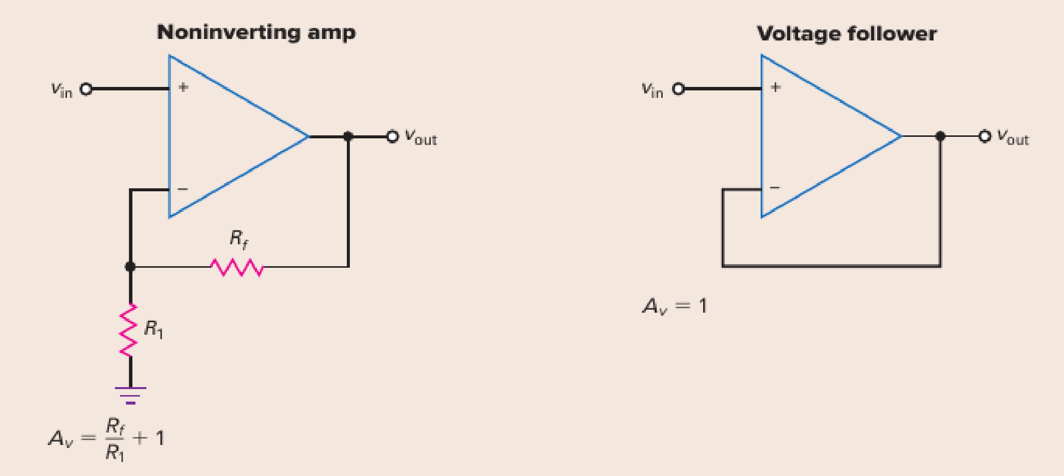
- Pertanyaan:
  - Jika rangkaian voltage follower di samping dibuat dengan Multisim, tegangan output di 1 Ω adalah 9.95 mV. Tentukan berapa impedansi output closed-loop?

Ringkasan



Inverting amp
R_f
R_1
v_{in}
v_{out}
$A_v = -\frac{R_f}{R_1}$
Summing amp
R_f
R_1
R_2
R_3
v_1
v_2
v_3
v_{out}
$v_{out} = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \frac{R_f}{R_3}v_3\right)$

Ringkasan



Noninverting amp
v_{in}
v_{out}
R_f
R_1
$A_v = \frac{R_f}{R_1} + 1$
Voltage follower
v_{in}
v_{out}
$A_v = 1$

Linear IC

- Op amp : $\frac{1}{3}$ bagian dari IC
- Linear IC : op amp, audio amplifier, video amplifier, voltage regulator

Tabel Parameter Op Amp saat 25°

Number	V_{in} max, mV	$I_{in(bias)}$ max, nA	$I_{in(off)}$ max, nA	I_{out} max, mA	f_{unity} typ, MHz	S_R typ, V/μs	A_{VOL} typ, dB	CMRR min, dB	PSRR min, dB	Drift typ, μV/°C	Description of Op Amps
LF353	10	0.2	0.1	10	4	13	88	70	−76	10	Dual BIFET
LF356	5	0.2	0.05	20	5	12	94	85	−85	5	BIFET, wideband
LF411A	0.5	200	100	20	4	15	88	80	−80	10	Low offset BIFET
LM301A	7.5	250	50	10	1+	0.5+	108	70	−70	30	External compensation
LM318	10	500	200	10	15	70	86	70	−65	—	High speed, high slew rate
LM324	4	10	2	5	0.1	0.05	94	80	−90	10	Low-power quad
LM348	6	500	200	25	1	0.5	100	70	−70	—	Quad 741
LM675	10	2 μA*	500	3 A†	5.5	8	90	70	−70	25	High-power, 25 W out
LM741C	6	500	200	25	1	0.5	100	70	−70	—	Original classic
LM747C	6	500	200	25	1	0.5	100	70	−70	—	Dual 741
LM833	5	1 mA*	200	10	15	7	90	80	−80	2	Low noise
LM1458	6	500	200	20	1	0.5	104	70	−77	—	Dual
LM3876	15	1 μA*	0.2 μA*	6 A†	8	11	120	80	−85	(−)	Audio power amp, 56W
LM7171	1	10 μA*	4 μA*	100	200	4100	80	85	−85	35	Very high-speed amp
OP-07A	0.025	2	1	10	0.6	0.17	110	110	−100	0.6	Precision
OP-42E	0.75	0.2	0.04	25	10	58	114	88	−86	10	High-speed BIFET
TL072	10	0.2	0.05	10	3	13	88	70	−70	10	Low-noise BIFET dual
TL074	10	0.2	0.05	10	3	13	88	70	−70	10	Low-noise BIFET quad
TL082	3	0.2	0.01	10	3	13	94	80	−80	10	Low-noise BIFET dual
TL084	3	0.2	0.01	10	3	13	94	80	−80	10	Low-noise BIFET quad

*For the LM675, LM833, LM3876 and LM7171, this value is commonly expressed in microamperes.

†For the LM675 and LM3876, this value is commonly expressed in amperes.

Power Supply Rejection Ration (PSRR)

- Persamaan PSRR:

$$PSRR = \frac{\Delta V_{in(off)}}{\Delta V_S} \tag{17}$$

- PSRR dari LF353 = -76 dB $\rightarrow$ PSRR = $10^(-76/20) = 0.000158 = 158\ \mu$V/V
- Setiap perubahan pada tegangan supply sebesar 1 V akan menyebabkan perubahan tegangan offset input sebesar 158 μV

Drift

- Koefisien temperatur dari tegangan offset input
- Seberapa banyak tegangan offset input akan meningkat karena temperatur
- Drift dari LF353 $= 10\ \mu\text{V}/^\circ\text{C} \rightarrow$ tegangan offset input akan meningkat sebesar 10 μV untuk setiap kenaikan 1 $^\circ$C
- Jika temperatur internal dari op amp meningkat sebesar 50 $^\circ$C maka tegangan offset input dari LF353 meningkat sebesar 500 μV

Audio Amplifiers

- Preamps = audio amplifier dengan daya output < 50 mW
- Front-end audio system
- Mengurangi low noise dari optical sensors, magnetic tape heads, microphones, dll
- Contoh:
  - LM833: low-noise dual preamp, $A_v = 110$ dB, 27-V power bandwidth 120 kHz, input berupa diff amp

Audio Amplifiers

- Medium-level audio amplifiers = output power 50 mW - 500 mW
- Near output end
- Portable electonic devices: cell phones, CD player
- Contoh:
  - LM4818 audio power amplifier: output power 350 mW

Audio Amplifiers

- Output power > 500 mW
- High-fidelity amplifier, intercoms, AM-FM radio
- Contoh:
  - LM380: $A_v = 34$ dB, bandwidth 100 kHz, output power 2 W
  - LM4756: $A_v = 30$ dB, output power 7 W/channel

Video Amplifiers

- Wideband amplifier
- Flat response (constant decibel voltage gain)
- Very broad range of frequencies
- Applications in which the range of input frequencies is very large: analog oscilloscopes, video cameras, copiers and scanners, and HDTV amplifiers
- Contoh:
  - LM7171: very high-speed amplifier, wide unity-gain bandwidth of 200 MHz, slew rate of 4100 $V/\mu S$
  - NE592: voltage gain 52 dB, cutoff frequency 40 MHz, voltage gains and bandwidths dapat diatur dengan menghubungkan external resistors yang berbeda sehingga menjadi 90 MHz
  - MC1553: gain 52 dB, bandwidth 20 MHz, adjusted by changing external components
  - LM733: up to 20-dB gain, bandwidth of 120 MHz (adjusted by changing external components)

Voltage Regulator

- Rectifier $\rightarrow$ dc voltage $+$ ripple $\rightarrow$ voltage regulator
- DC voltage $\propto$ line voltage
- Perubahan 10% dari line voltage $\propto$ perubahan 10% DC voltage $\leftarrow$ ini terlalu besar
- LM340 series $\rightarrow$ menahan perubahan 0.01%, positive/negative output, adjustable output voltage, and short-circuit protection.

TERIMA KASIH