102

EE 2245 Microelectronics Labs

Lab 4: Active Filter Design (4 weeks)

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Design Problem I:

You are required to implement a biquad band-pass filter shown in Fig. 1 with the following specifications:

(1) Band-pass frequency = 3 kHz (with a variation less than ±2%); Note: Band-pass frequency is the frequency where $|v_{BP}(j\omega)/\ v_i(j\omega)|$ has the maximum value.

(2) Quality factor ≥ 8

$H(s)=\frac{\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2}$, $Q=\frac{1}{2\zeta}$

Note:

(1) **Please show your analysis, including the input-output relationship of $v_{BP}(s)/v_i(s)$, the band-pass frequency, and the quality factor, to a teaching assistant before implementing the circuit.**

Hint: You can start with the KCL analysis at the "-" node of the 1st op amp.

(2) Demonstrate your result to me or a TA.

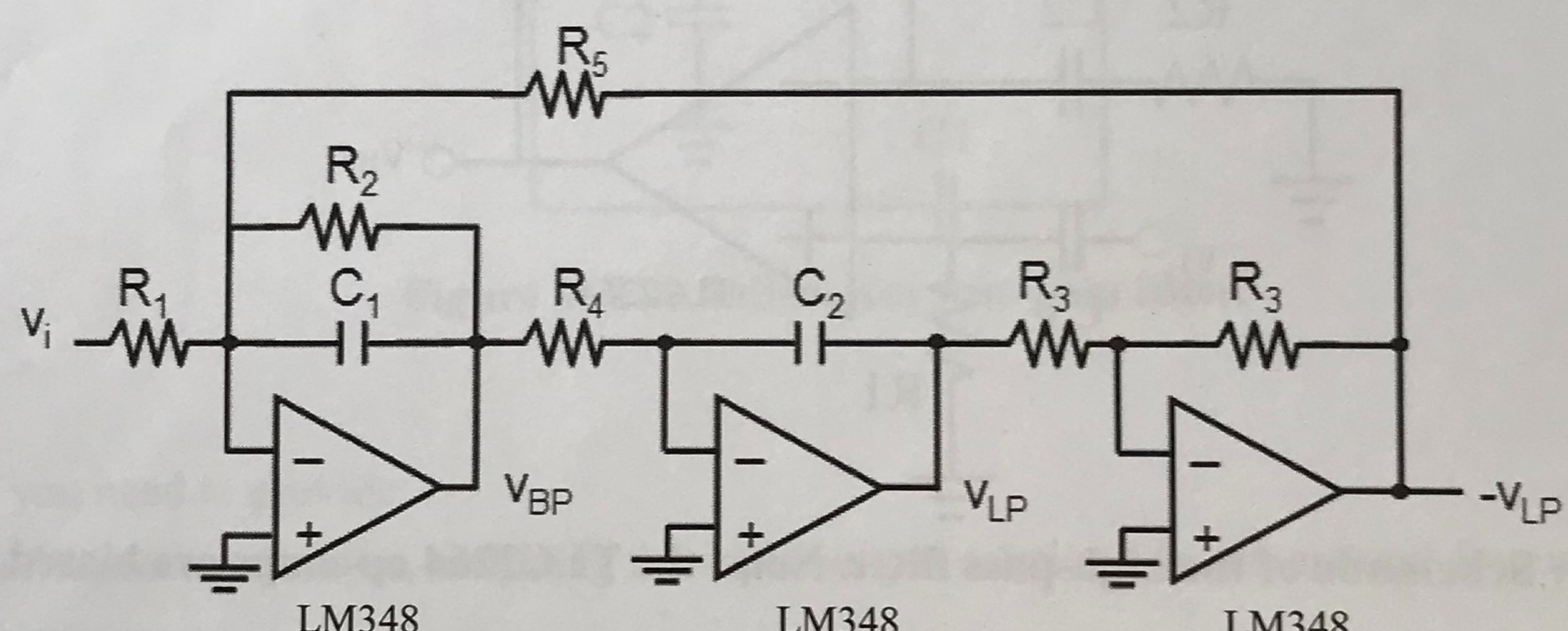


Figure 1: Schematic of the biquad filter. Note: the LM348 op-amps are biased at ±18 V.

For your implementation, please use resistor values in the range of $2\ k\Omega \leq R_i \leq 500\ k\Omega$, and use $C_1 = 1$ nF. The amplitude of the input voltage should be kept at a proper value to get enough output signals at low frequencies and avoid saturation of the high-Q circuit at the band-pass frequency.

In the report, you need to provide:

(1) Analysis of the band-pass filter, including the input-output relationship, the band-pass frequency, and the quality factor.

(2) Complete design process (how do you select the passive elements).

(3) Measured frequency response (Gain vs. frequency).

Design Problem II:

請注意：Design Problems II, III, and IV 所用的 op-amp 與 Design Problem I 不同。Problem IV 將整合 II、 III 部份進行 ECG 量測，以下電路量完不要馬上拆。

You are required to implement an active high-pass filter shown in Fig. 2 with the following specifications:

(1) High-pass corner frequency = 1 Hz (i.e. Design both poles of the filter to locate at 1Hz);

(2) Flat-band voltage gain = 100 (V/V) (maximum tolerable gain error = ±10%); 102 ⇒ 40、17 dB

(3) Input impedance ≥ 1 MΩ at 1 Hz. 24 ⇒

Note:

(1) **Please show your analysis, including the input-output relationship of $v_{HP}(s)/v_i(s)$, the pole frequency, the flat-band voltage gain, and the input impedance to a teaching assistant before implementing the circuit.**

(2) **Demonstrate your result to me or a TA.**

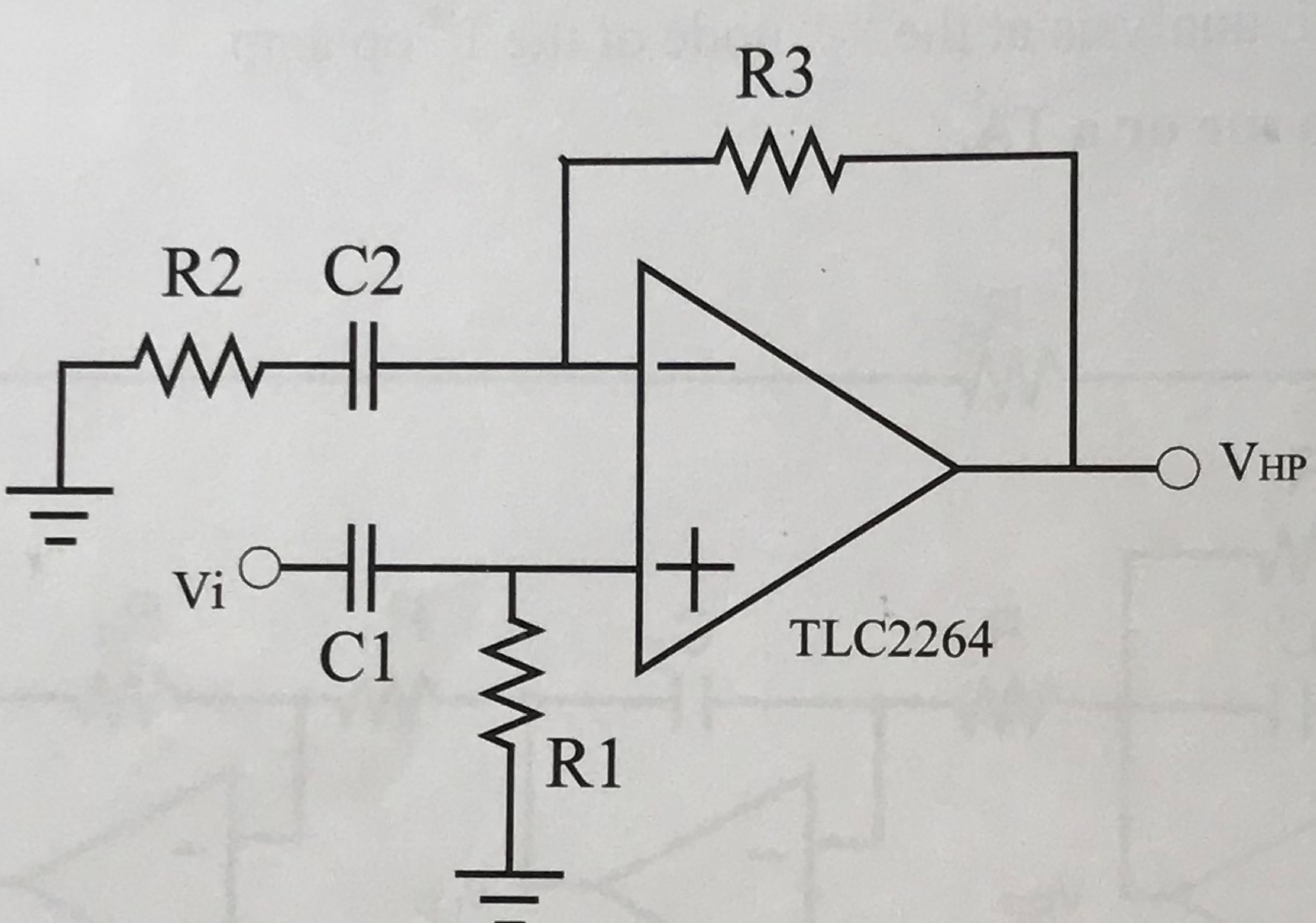


Figure 2: Schematic of the high-pass filter. Note: the TLC2264 op-amps are biased at ±8 V.

In the report, you need to provide:

(1) Analysis of the high-pass filter, including the input-output relationship, the pole frequency, the flat-band voltage gain, and the input impedance.

(2) Complete design process (how do you select the passive elements).

(3) Measured frequency response (Gain vs. frequency). The gain at 0.1 Hz, 1 Hz, and 10Hz must be measured.

(4) Does the measured gain response agree with your analysis by satisfying the following three conditions? (i) The flat-band voltage gain is 40 dB (with ±10% tolerance) at 10 Hz. (ii) The gain reduces by about 5dB at 1 Hz. (iii) The gain is smaller than 5 dB at 0.1 Hz. If any of the conditions is not satisfied, please discuss the reasons based on the derived input-output relationship and the real values of resistors and capacitors in your experiment.

Design Problem III:

You are required to implement the Sallen-Key low-pass filter shown in Fig. 3 with the following specifications:

(1) The natural frequency $20\text{ Hz} \leq f_n \leq 60\text{Hz}$ $(\omega_n = 2\pi f_n)$

(2) Flat-band voltage gain ≥ 3 (V/V);

(3) $R1 \geq 10\text{ k}\Omega$

Note:

(1) **<u>Please show your analysis, including the input-output relationship of $v_{LP}(s)/v_i(s)$, the natural frequency, the flat-band voltage gain to a teaching assistant before implementing the circuit.</u>**

(2) **Demonstrate your result to me or a TA.**

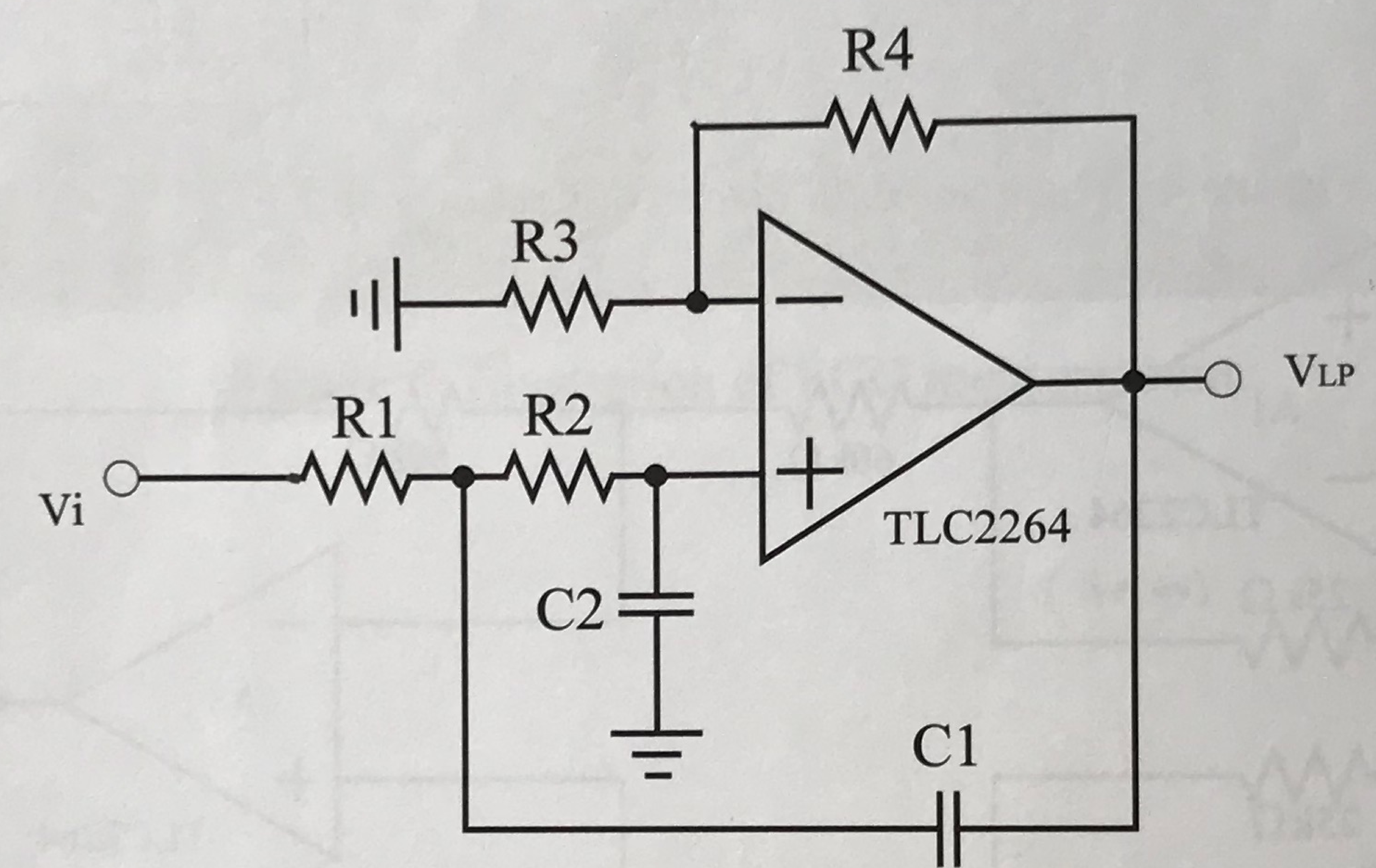


Figure 3: The Sallen-Key low-pass filter.

In the report, you need to provide:

(1) Analysis of the low-pass filter, including the input-output relationship, the natural frequency, and the flat-band voltage gain.

(2) Complete design process (how do you select the passive elements).

(3)Apply a 100-mV sinusoidal signal at the designed natural frequency (f_n) to the input V_i, measure the phase difference between V_i and V_{LP}. Is the phase difference equal to 90°?

(4) Measured frequency response (Gain vs. frequency). The gain at 1 Hz, 10 Hz, your designed natural frequency, 60 Hz, and 100 Hz must be measured.

(5) Does the measured gain response agree with your analysis? If not, please discuss the reasons.

Design Problem IV:

In this task, you are going to integrate the filters designed in problem II and III to form an amplifier capable of recording electrocardiograms (ECGs), as shown by Fig. 4. An instrumentation amplifier (INA) is added at the front end to remove common-mode interferences. Fig. 5 shows the circuit diagram of INA, where the external R_G determines the voltage gain.

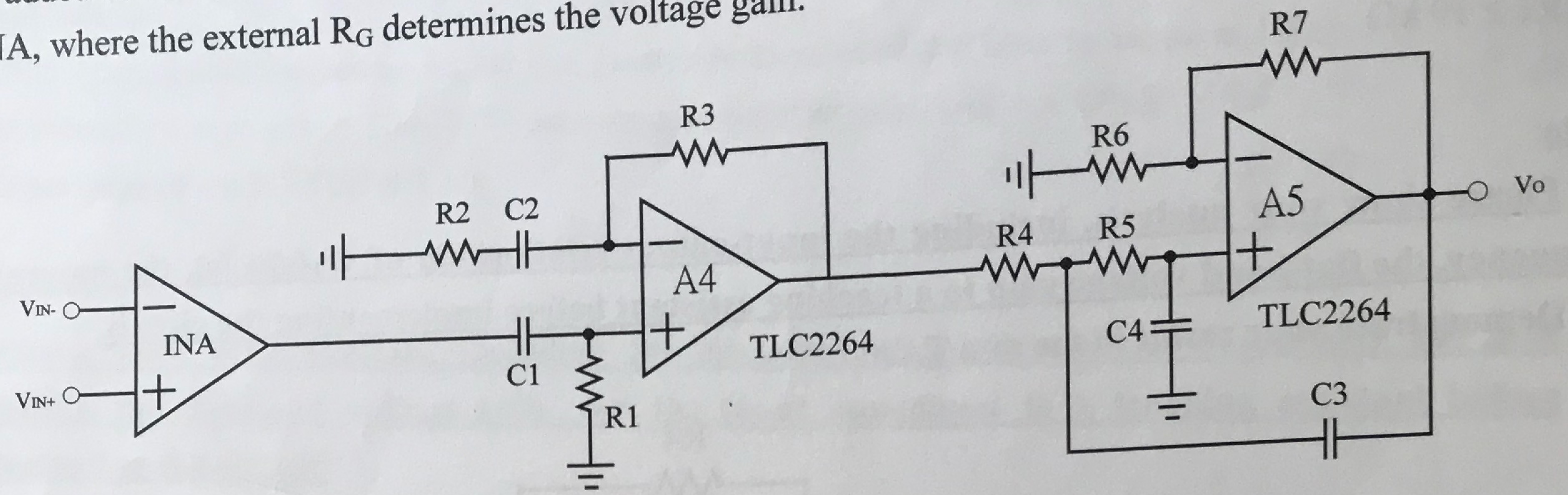


Figure 4: The complete circuit for recording ECG.

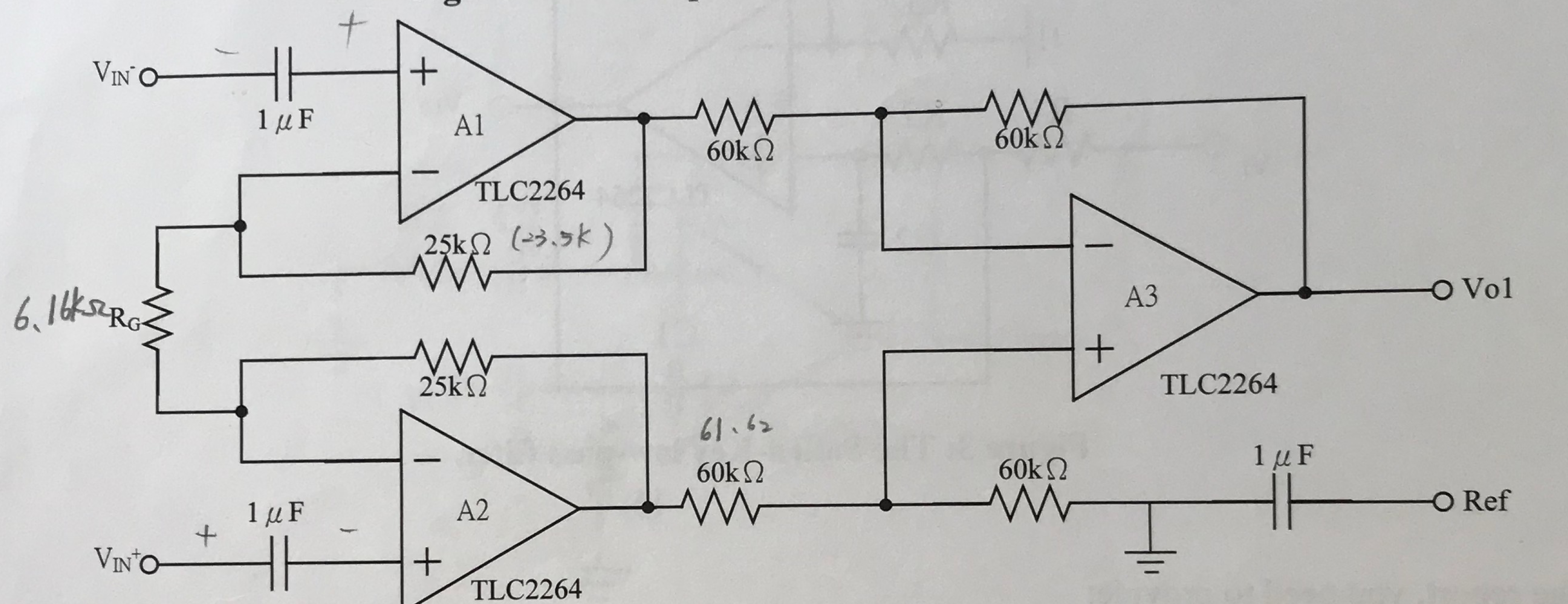


Figure 5: The circuit diagram of the instrumentation amplifier.

Experiments :

(1) Design R_G to achieve a voltage gain greater than 6 (V/V) for the circuit in Fig. 5. Apply a 10-mV, 10-Hz sinusoidal signal across the differential input (V_{IN}^+, V_{IN}^-). Measure the corresponding output at V_{O1} and answer the following questions.

(a) How much is the voltage gain $V_{O1} / (V_{IN}^+ - V_{IN}^-)$?

(b) Does the output signal contain any DC offset?

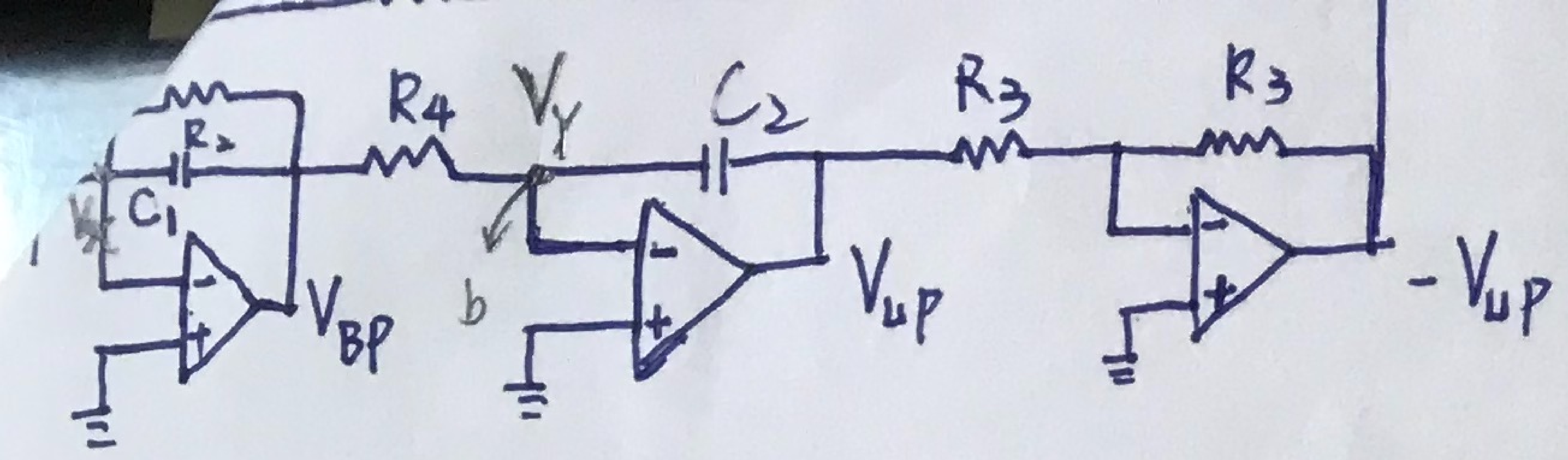
If yes, please discuss the main amplifier(s)(A1-A5) that contribute the DC offset at the output.

(2) Connect the input to wet electrodes and measure your own electrocardiograms as Fig.6. Does the output contain DC offsets or interference? Please answer the following questions

(a)What is the main frequency component of the interference?

(b)How could we reduce the interference?

You must show TAs your measured ECG signals before leaving the lab



@ node a, KCL:

$$\frac{V_i - V_x}{R_1} = \frac{V_x - (-V_{LP})}{R_5} + \frac{V_x - V_{BP}}{R_2} + \frac{V_x - V_{BP}}{1/sC_1}$$

$$\Rightarrow \frac{V_i}{R_1} + \frac{V_{BP}}{R_2} + sC_1 V_{BP} - \frac{V_{LP}}{R_5} = 0 \quad — (1)$$

@ node b, KCL:

$$\frac{V_{BP} - V_Y}{R_4} + \frac{V_Y - V_{LP}}{1/sC_2} = 0$$

$$\Rightarrow V_{LP} = \frac{-1}{sR_4C_2} V_{BP} \quad — (2)$$

(2) 代入 (1)

$$\frac{1}{R_1} + \frac{V_{BP}(s)}{V_i(s)}\left(\frac{1}{R_2} + sC_1 + \frac{1}{sR_4R_5C_2}\right) = 0$$

$$\Rightarrow \frac{V_{BP}(s)}{V_i(s)} = \frac{-1}{R_1} \times \frac{1}{\frac{1}{R_2} + sC_1 + \frac{1}{sR_4R_5C_2}}$$

$$= \frac{-s}{R_1C_1} \times \frac{1}{s^2 + 2\frac{1}{2R_2C_1}s + \frac{1}{R_4R_5C_1C_2}}$$ (I/O relationship)

$$\therefore \omega_n = \frac{1}{\sqrt{R_4R_5C_1C_2}}$$ (band-pass frequency), $$\zeta = \frac{\sqrt{R_4R_5C_1C_2}}{2R_2C_1} = \frac{\sqrt{R_4R_5C_2}}{2R_2\sqrt{C_1}}$$

(Quality factor)

$$Q = \frac{1}{2\zeta} = \frac{R_2C_1}{\sqrt{R_4R_5C_2C_1}} = R_2C_1\omega_n$$

$$\omega_n = \frac{1}{\sqrt{R_4R_5C_1C_2}} = 3K \cdot 2\pi$$

$$Q = \frac{R_2\sqrt{C_1}}{\sqrt{R_4R_5C_2}} = R_2C_1\omega_n$$

且 $C_1 = 1nF$, (by 題目)

$$Q = R_2 \cdot 1nF \cdot 6k\pi \geq 8$$

$$\therefore R_2 \geq 424.182\ \Omega \quad \#$$

$$\omega_n = 6K\pi = \frac{1}{\sqrt{R_4R_5C_1C_2}}$$

$$\Rightarrow R_4R_5C_2 = 2.814$$

choose $C_2 = 2nF$ #

$\therefore R_4 = 33k\Omega$ #

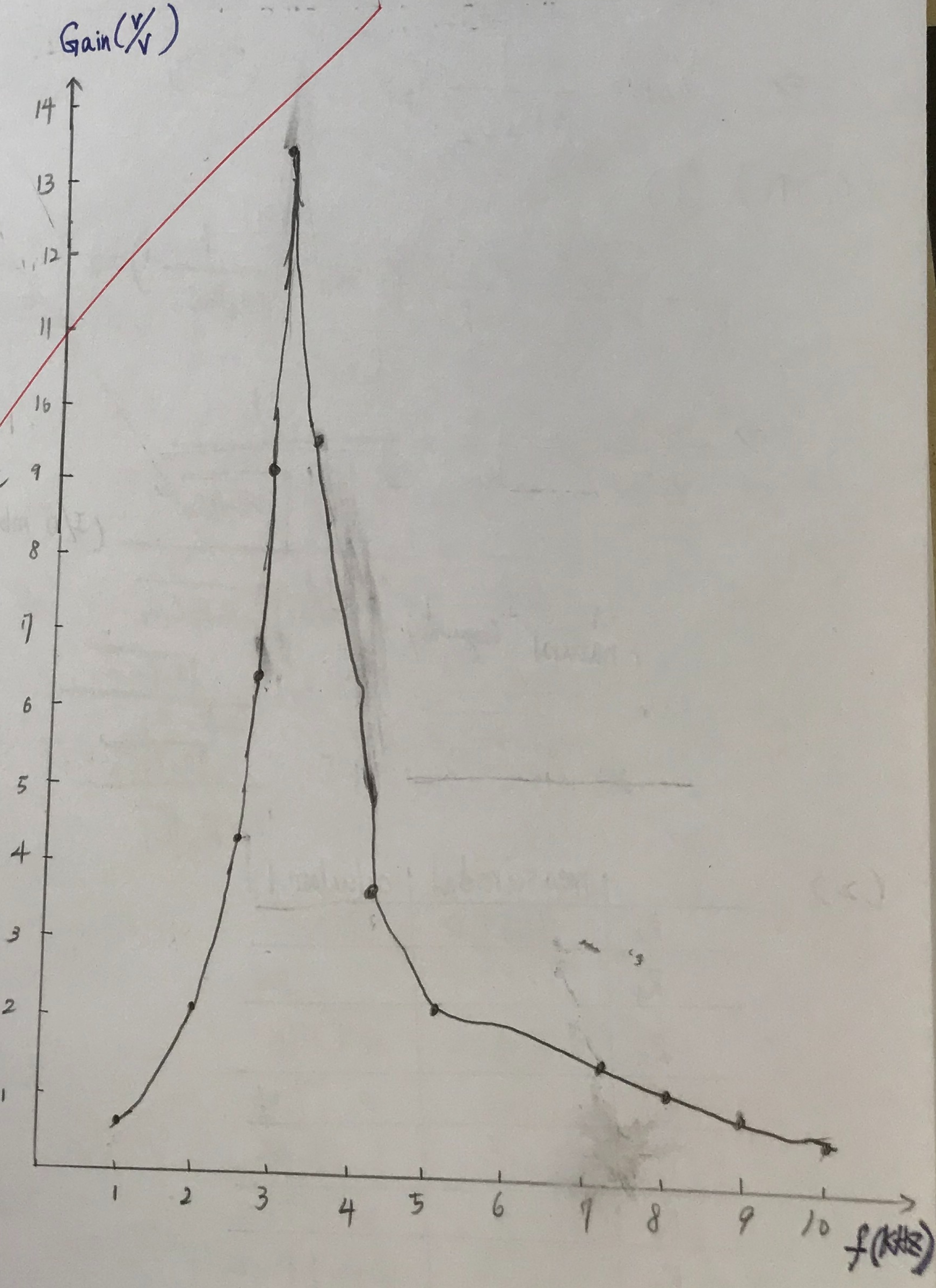
$R_5 = 43k\Omega$ #

(2)

	calculated	measured
R_2	475kΩ	475kΩ
R_4	33kΩ	32.75kΩ
R_5	43kΩ	44.17K
C_1	1nF	0.99nF
C_2	2nF	1.98nF
R_1	30kΩ	30.27kΩ
R_3	20kΩ	20.1kΩ

(3)

f (KHz)	$V_{i(p-p)}$	$V_{BP(p-p)}$	Gain (V/V)
1	1	0.66	0.66
2	1	2.04	2.04
2.5	1	4.2	4.2
2.7	1	6.48	6.48
2.8	1	9.1	9.1
2.9	1	10.2	10.2
3	1	13.4	13.4
3.1	1	12.9	12.9
3.3	1	9.2	9.2
3.5	1	6.56	6.56
4	1	3.76	3.76
4.5	1	2.72	2.72
5	1	2.16	2.16
6	1	1.6	1.6
7	1	1.36	1.36
8	1	1.12	1.12
9	1	0.96	0.96
10	1	0.636	0.636



How to achieve Q = 8:

(1) By formula $Q = \frac{R_2 C_1}{\sqrt{R_4 R_5 C_1 C_2}}$, the easiest way is to increase R_2. I only need to make sure $R_2 \leq 500\Omega$ (According to the problem)

(2) By observation, R_4 and R_5 should be as close as possible.

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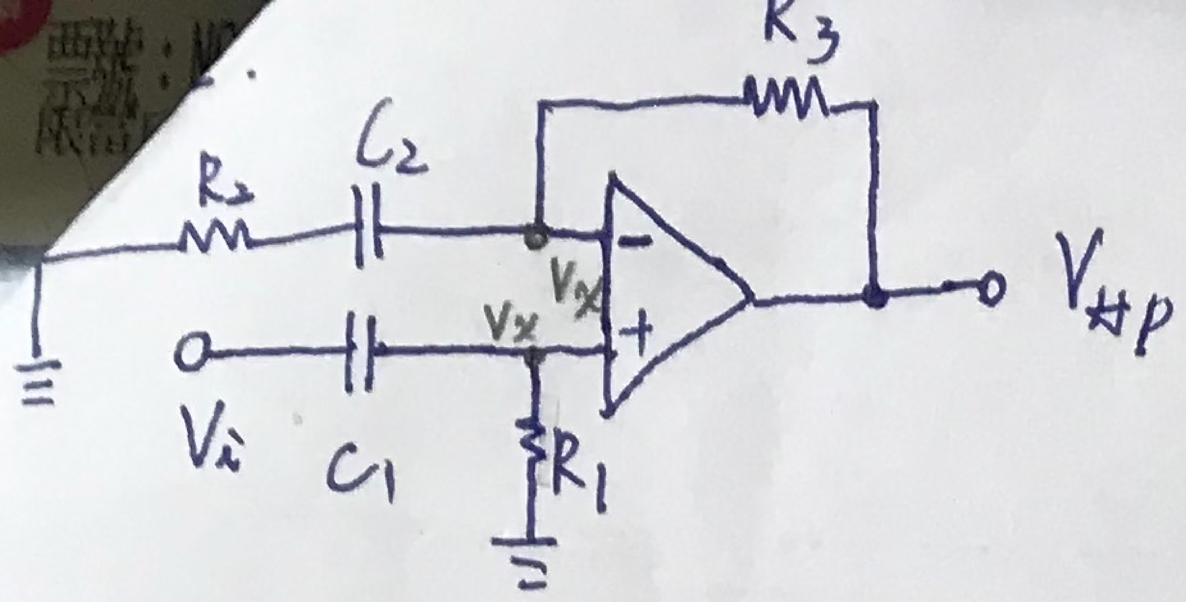


(1)

$$\frac{V_{HP}-V_x}{R_3} = \frac{V_x}{R_2+\frac{1}{sC_2}} \Rightarrow \frac{V_{HP}}{R_3} = \frac{V_x}{R_3} + \frac{V_x}{R_2+\frac{1}{sC_2}} \quad -(1)$$

$$V_x = V_i \times \frac{R_1}{\frac{1}{sC_1}+R_1} \quad -(2)$$

With (1), (2)

relationship:

$$\frac{V_{HP}(s)}{V_i(s)} = \left(\frac{R_2+R_3+\frac{1}{sC_2}}{R_2R_3+\frac{R_3}{sC_2}}\right)\times\frac{R_1R_3}{\frac{1}{sC_1}+R_1} = \frac{sC_2(R_2+R_3)+1}{sC_2R_2+1}\times\frac{sC_1R_1}{1+sC_1R_1}$$

$$= \frac{s^2C_1C_2R_1(R_2+R_3)+sC_1R_1}{(1+sC_1R_1)(1+sC_2R_2)}$$

$$= \frac{s[sC_1C_2R_1(R_2+R_3)+C_1R_1]}{(1+sR_1C_1)(1+sR_2C_2)} \Rightarrow \omega_1 = \frac{1}{C_1R_1},\quad \omega_2 = \frac{1}{C_2R_2}$$

pole frequency:

$$\begin{cases} f_1 = \dfrac{1}{2\pi C_1R_1} \\ f_2 = \dfrac{1}{2\pi C_2R_2} \end{cases}$$ #

Rin:

$$R_1+\frac{1}{sC_1}$$ #

flat-band voltage gain.

$$\left|\frac{V_{HP}(s)}{V_i(s)}\right|_{s\to\infty} = \frac{R_1C_1C_2(R_2+R_3)}{R_1C_1R_2C_2} = \frac{R_2+R_3}{R_2}$$ #

(2)

	calculated	measured
R_1	750kΩ	750.9kΩ
R_2	7500 Ω	7550 Ω
R_3	742.5kΩ	750kΩ
C_1	0.21μF	0.207μF
C_2	21.2μF	21.4μF

$$\begin{cases} f_1 = f_2 = 1\,Hz \Rightarrow C_1R_1 = C_2R_2 = \frac{1}{2\pi} \\ \frac{R_2+R_3}{R_2} = 100 \Rightarrow R_3 = 99R_2 \\ R_{in} = R_1+\frac{1}{sC_1} \Rightarrow \left|R_1+\frac{1}{j2\pi C_1}\right| = \sqrt{R_1^2+R_1^2} = \sqrt{2}\cdot R_1 > 1M\Omega \end{cases}$$

@ f=1Hz

$$\Rightarrow R_1 \geq \frac{10^6}{\sqrt{2}} \approx 707\,k\Omega$$

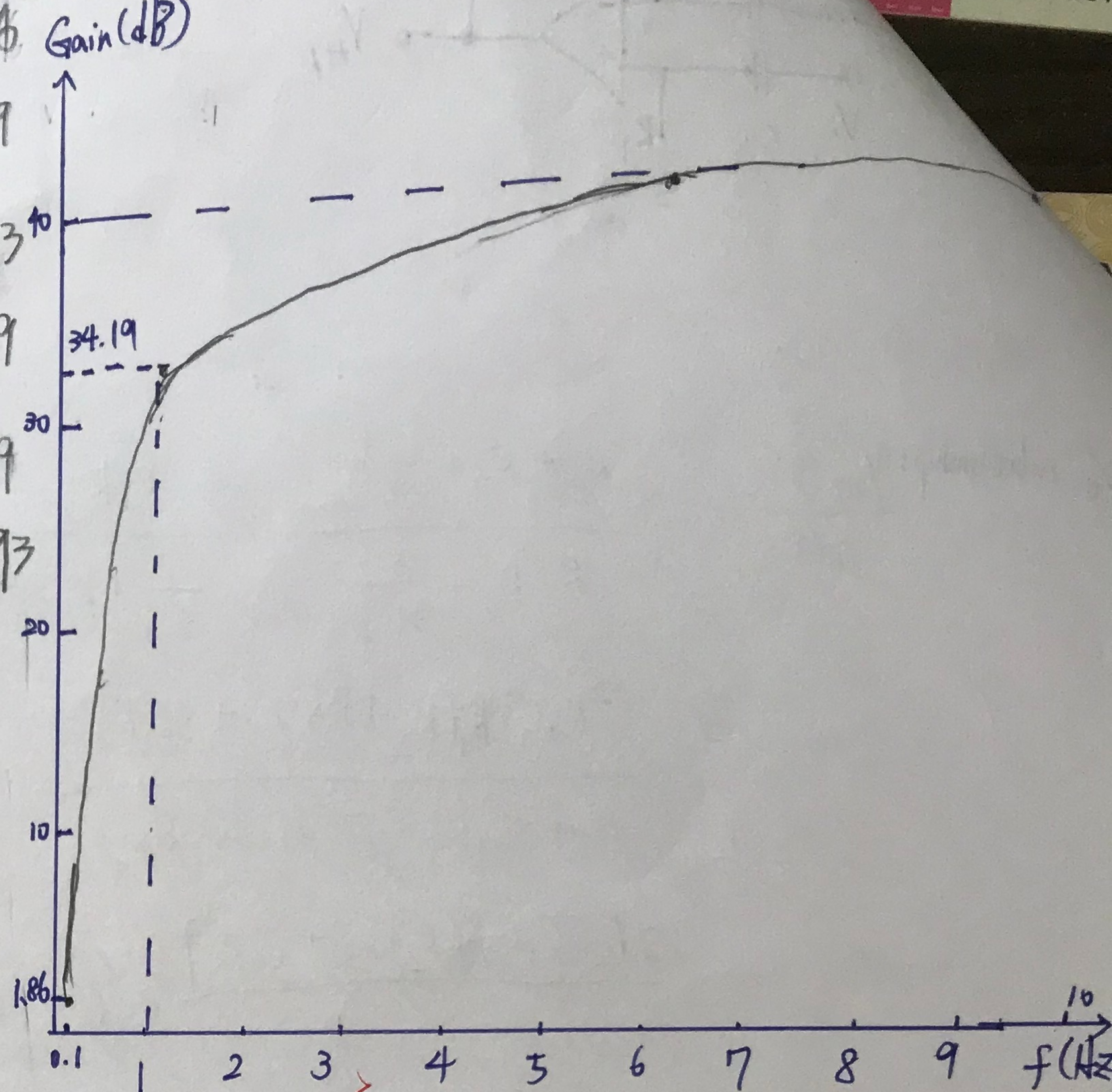
Choose $R_1 = 750k \Rightarrow C_1 = \frac{1}{2\pi}/750k = 0.21\mu F$

choose $R_2 = 7500 \Rightarrow C_2 = \frac{1}{2\pi}/R_2 = 21.2\mu F$

$R_3 = 99R_2 = 742.5k\Omega$

3)

frequency (Hz)	$V_{in(p-p)}$ (V)	$V_{out(p-p)}$ (V)	Gain (dB)
0.1	100m	124m	1.86
1	100m	5.12	34.19
2	100m	8.16	38.23
3	100m	9.12	39.19
4	100m	9.44	39.49
6	100m	9.92	39.93
8	100m	10.1	40
10	100m	10.1	40
20	100m	10.1	40
100	100m	10.1	40



(4)

(i) at 10 Hz, measured gain: 40 dB (V)

(ii) at 1 Hz, measured gain: 34.19 dB (reduces by 5.8 dB) (V)

(iii) at 0.1 Hz, measured gain: 1.86 dB (< 5 dB) (V)

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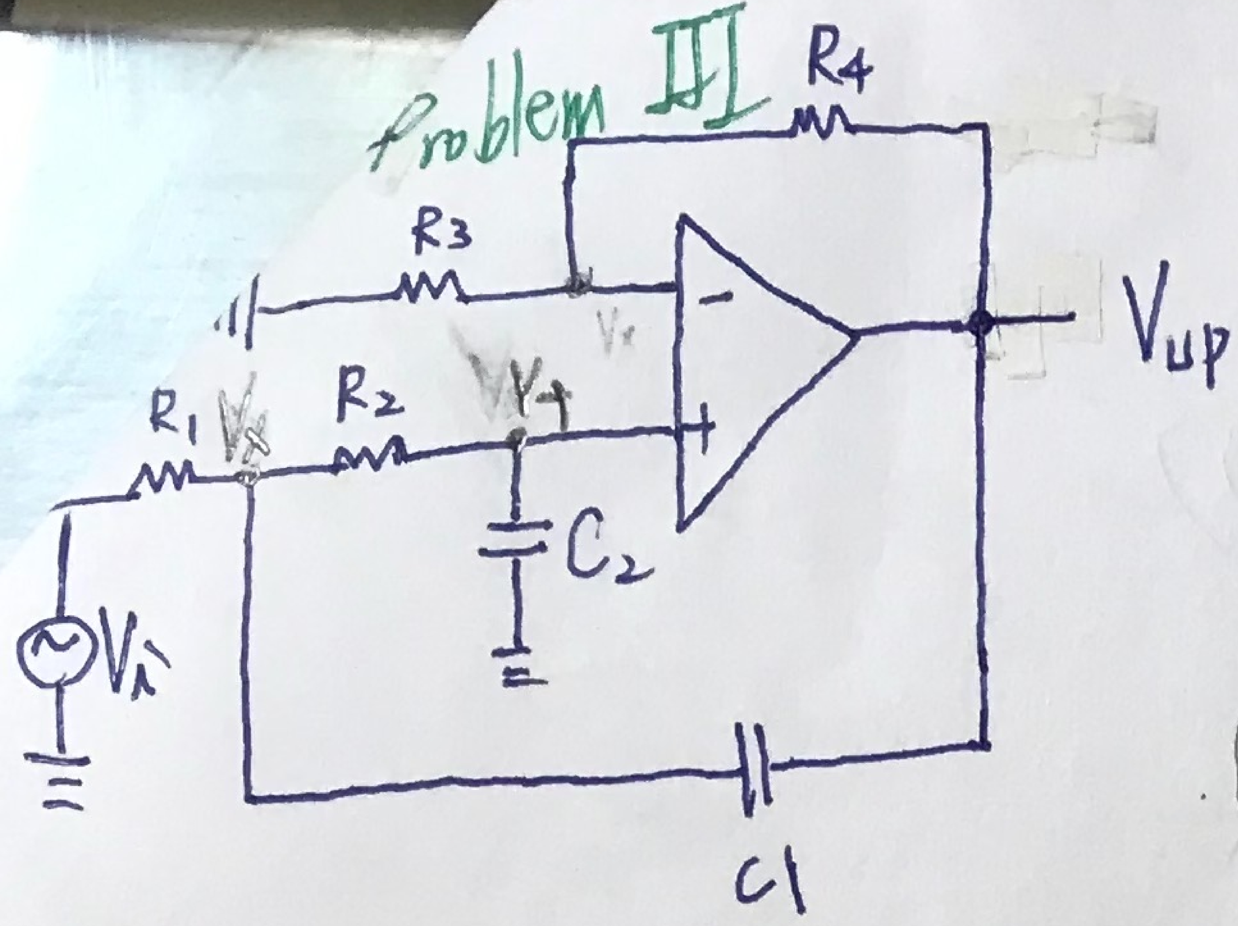
Problem III



(1) $K = 1 + \frac{R_4}{R_3}$

$V_{up} = K V_+$

$= K\left(\frac{1}{R_2 C_2 s} \cdot V_x\right)$

Summing currents at node V_x :

$$\frac{V_i - V_x}{R_1} + \frac{V_+ - V_x}{R_2} + \frac{V_{up} - V_x}{1/sC_1} = 0$$

$$\Rightarrow \frac{V_{up}(s)}{V_i(s)} = \frac{K}{R_1C_1R_2C_2s^2 + [(1-K)R_1C_1 + R_1C_2 + R_2C_2]s + 1}$$ (I/O relationship)

(natural frequency)

$$\Rightarrow \omega_n = \frac{1}{\sqrt{R_1C_1R_2C_2}} \qquad Q = \frac{1}{2\zeta} = \frac{\sqrt{R_1C_1R_2C_2}}{(1-K)R_1C_1 + R_1C_2 + R_2C_2}$$

(flat-band voltage gain)

$$\left.\frac{V_{up}(s)}{V_i(s)}\right|_{s=0} = K = 1 + \frac{R_4}{R_3}$$

(2)

	calculated	measured
C_1	100nF	102nF
C_2	1μF	1.03 μF
R_1	15kΩ	14.905kΩ
R_2	10kΩ	9.926kΩ
R_3	10kΩ	9.902 kΩ
R_4	50kΩ	51.19kΩ

choose $f_n \approx 40$ Hz，且 $R_1 \geq 10k\Omega$

$\Rightarrow R_1 = 15k\Omega$ $R_2 = 10k\Omega$, $C_1 = 100nF$, $C_2 = 1\mu F$

$K \geq 3 \Rightarrow 1 + \frac{R_4}{R_3} \geq 3$

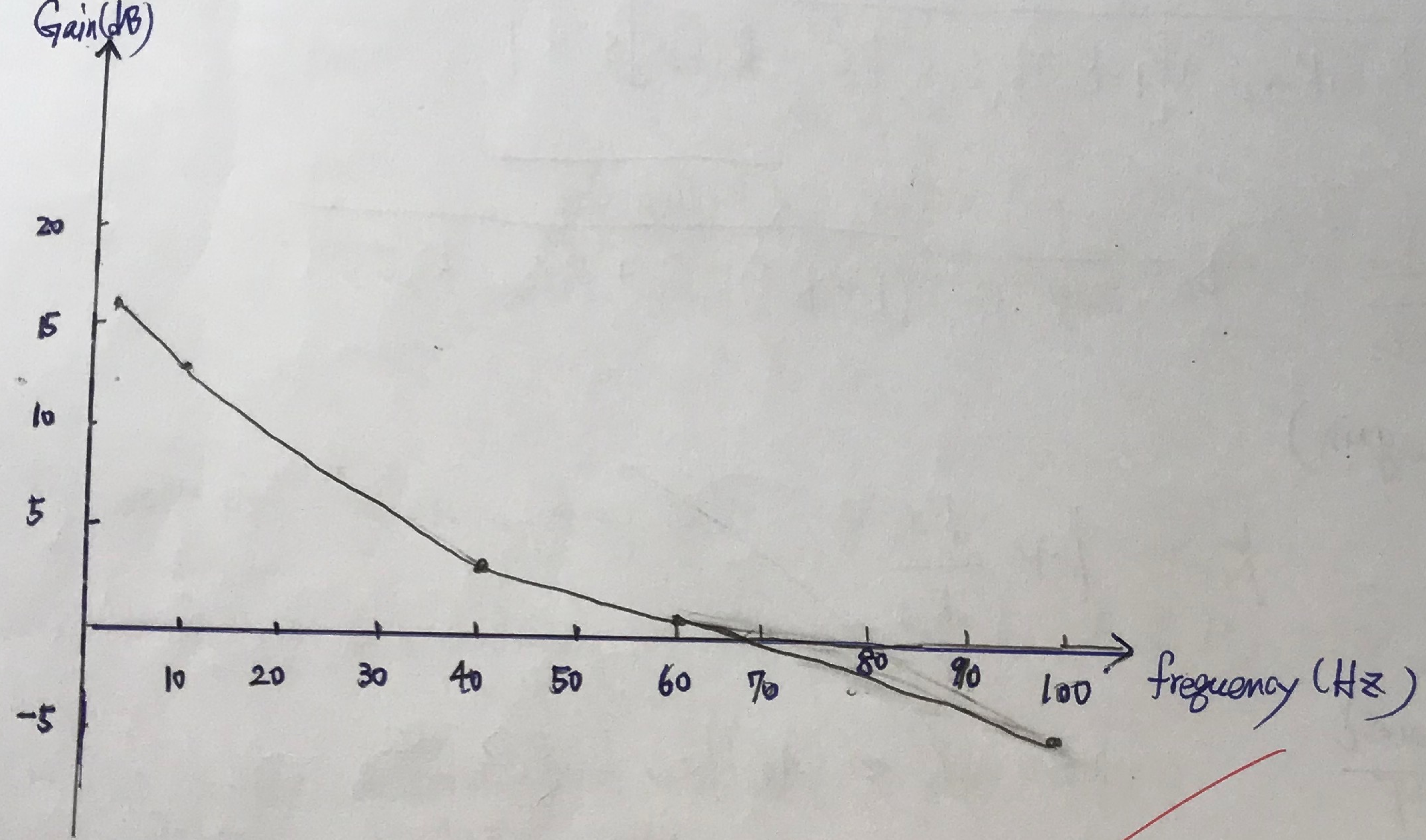
$\Rightarrow$ choose $\begin{cases} R_4 = 50k\Omega \\ R_3 = 10k\Omega \end{cases}$

(3)

$$\underset{\Delta t}{\underline{6.4\times10^{-3}}} \times \underset{\frac{1}{T}}{\underline{40}} \times 360 = 92.16^\circ \approx 90^\circ$$

(4)

frequency (Hz)	$V_{in(p-p)}$ (V)	$V_{o(p-p)}$ (V)	Gain (dB)
1	0.1	0.632	16
10	0.1	0.448	13.03
40	0.1	0.156	3.86
60	0.1	0.102	0.17
100	0.1	0.058	-4.7



(5)

My analysis: $\text{gain} = 1 + \frac{R_4}{R_3} = 6$ (V/V)

Measured gain at 1 Hz (Flat-band gain) = 6.32 (V/V), I think it's because $V_{in(p-p)}$ may be larger than 0.1 V, but I didn't measure the exact value.

Therefore there is error $\frac{6.32-6}{6} \approx 5.3\%$ #

Problem IV.

(1) $V_{o1} = \left(1 + \frac{2R_1}{R_G}\right)(V_{in}^+ - V_{in}^-)$

$\Rightarrow \frac{V_{o1}}{V_{in}^+ - V_{in}^-} = 1 + \frac{2R_1}{R_G} \geq 6$ (R_1 = 25kΩ)

∴ Choose $R_G = 6k\Omega$

	Calculated	measured
R_G	6 kΩ	6.09 kΩ

(a) $V_{o1} / (V_{in}^+ - V_{in}^-) = 9 (V/V)$ my design value is $1 + \frac{50}{6} \approx 9.3 (V/V)$

So the experimental result is quite consistent with calculated result.

(b) DC offset = 180 mV, offset may come from A3, input 為 V_{in}^+、V_{in}^- 且是 ac signal 所以本身帶有一點 DC offset。但 output 在 A3 的 V_{o1}，因此有 DC offset

(2)
(a) The main frequency of interference is 60Hz.

(b) ① 貼片的位置盡量貼在脈搏明顯的地方

② Change amplifier's [in problem III (A5)] natural frequency to lower frequency to filter 60 Hz interference frequency.

波形圖附在最後一頁!


Tek
Stop
M Pos: 0.000s
AUTOSET
CH1
平均值
?
CH1
峰對峰值
?
取消自動設定
CH1 200mV
M 100ms
12-Nov-19 17:27
CH1 ⁄ -39.3mV
<10Hz
REF MENU
SAVE
PRINT
TRIG VIEW
CH 1 MENU
MATH MENU
CH 2 MENU
PROBE CHECK
CH 1
CH 2
USB Flash Drive
PROBE COMP ~5V@1kHz