UNIVERSITY ELECTRICAL ENGINEERING • EXERCISE SHEET

5.6 Op-amp feedback circuits

Name: _____ Class: _____ Date: _____ **Total: 20 marks**

KEY WORDS negative feedback • loop gain • transimpedance amplifier • gain-bandwidth product

Objective

Analyse the four feedback topologies, apply the gain-bandwidth product, and explain (with numbers) why loop gain makes closed-loop gain precise.

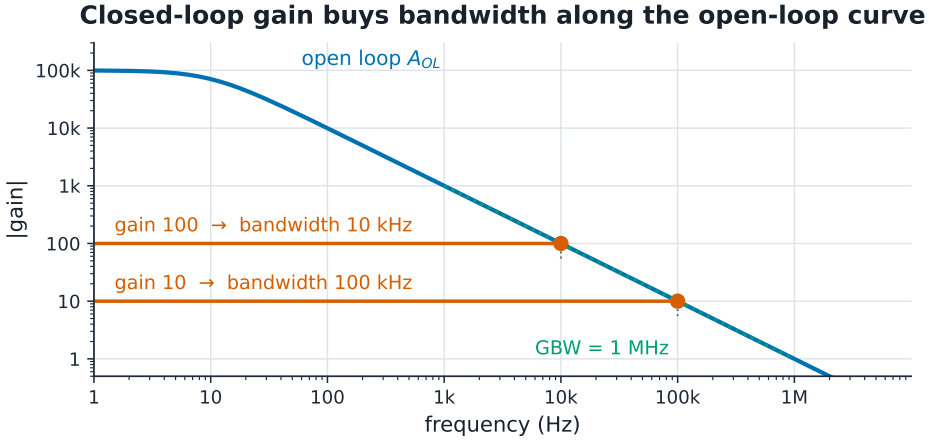
1 Key knowledge and worked examples

The four topologies, one idea

With **negative feedback** and high loop gain, the closed-loop gain is set by the feedback network:

- Inverting: $A = -R_f/R_{in}$ (input R = R_{in}).
- Non-inverting: $A = 1 + R_f/R_{in}$ (input R $\to \infty$).
- **Transimpedance** (current in): $v_o = -I_p \cdot R_f$.
- Summing: $v_o = -(v_1 R_f/R_1 + v_2 R_f/R_2)$.

Worked example. The transimpedance photodiode amp with $R_f = 100k\Omega$ and photocurrent 2 µA: $v_o = -0.2V$. The check: the inverting input is a virtual ground, so ALL the photocurrent flows through R_f – the output voltage is that current times that resistor, nothing else.



Closed-loop gain buys bandwidth along the open-loop curve.

Gain-bandwidth: the hyperbola

The **gain-bandwidth product** (GBW) is constant: closed-loop bandwidth = GBW / closed-loop gain. **Worked example**: GBW = 1 MHz – gain 100× gives 10 kHz; gain 10× gives 100 kHz; gain 1× (follower) gives 1 MHz. The product stays 1 MHz along the whole hyperbola, so speed costs gain one-for-one.

Why feedback makes gain precise

Open-loop gain A_{OL} varies with temperature and unit-to-unit spread; the closed-loop gain $A_{OL}/(1+A_{OL}\cdot\beta) \to 1/\beta$ when $A_{OL}\cdot\beta \gg 1$. **Worked example**: $A_{OL} = 100,000$, $\beta = 0.01$ (nominal closed-loop 100): exact $A = 100000/1001 = 99.9$ – 0.1% from the resistor-defined 100. Halve A_{OL}: `50000/501 = 99.8` – the closed-loop gain moved 0.1% while the chip's gain moved 50%. That insensitivity is the whole technology of precision analog.

2 Practice

2.1 An inverting amp with $R_f = 47k\Omega$, $R_{in} = 4.7k\Omega$: compute the gain and the input resistance. [2]

2.2 A non-inverting amp with $R_f = 39k\Omega$, $R_{in} = 1k\Omega$: compute the gain and the feedback factor β. [2]

2.3 A 5 mA (full-scale) current into a transimpedance amp must give 5 V: choose R_f. [2]

3 Exam-style questions

3.1 Design a summing amplifier: output $= -(2v_1 + v_2)$ with input resistance of the v_1 channel equal to 10 kΩ.

Choose all three resistors, then extend to make the output positive ($+(2v_1 + v_2)$) by adding a second inverting stage (choose its resistors). Compute the overall gain of each channel and verify with $v_1 = 0.5V$, $v_2 = 1.2V$. [7]

3.2 An op-amp has GBW = 2 MHz and open-loop gain 120 dB.

Compute the bandwidth at closed-loop gains 100×, 20× and 1×. Then compute the exact closed-loop gain at 20× nominal ($\beta = 1/20$) using $A_{OL}/(1 + A_{OL}\beta)$, and the gain error versus nominal. State the slew-rate concern: a 20× amp passing 50 kHz at 5 V peak needs what minimum slew rate ($SR = 2\pi f \cdot V_{peak}$), and does a 10 V/µs op-amp qualify? [7]

Solutions

2.1

- Gain `-47/4.7 = -10`; input R = R_{in} = 4.7 kΩ.

2.2

- Gain `1 + 39/1 = 40`; $\beta = R_{in}/(R_{in} + R_f) = 1/40 = 0.025$.

2.3

- $R_f = 5V/5mA = 1k\Omega$.

3.1

- Summing: $R_1 = 10k\Omega$ (v_1 channel, sets its input resistance); gain 2 → $R_f = 20k\Omega$; gain 1 for v_2 → $R_2 = 20k\Omega$.
- Second stage: unity inverting, two 10 kΩ (any equal pair).
- Channel gains: $2 \times 1 = 2$ through v_1, $1 \times 1 = 1$ through v_2 – net positive as required.
- Verify: $v_o = +(2 \times 0.5 + 1.2) = +2.2V$.

3.2

- Bandwidths: `2 MHz/100 = 20 kHz`; `/20 = 100 kHz`; `/1 = 2 MHz`.
- $A_{OL} = 10^(120/20) = 10^6$; exact gain `= 10^6/(1 + 10^6/20) = 10^6/50001 = 19.9996`.
- Gain error: `20 - 19.9996 = 0.0004` – 0.002% (loop gain $A_{OL} \cdot \beta = 50,000$ makes the error its reciprocal).
- Slew rate needed: $2\pi \times 50k \times 5 = 1.57V/\mu s$ – a 10 V/µs op-amp qualifies with 6× margin ✓.