Aalto University
School of Engineering

Mechatronics Machine Design (MMD)

MEC-E5001
Lecture 3
On Jan 21, 2020
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6 week spurt, stay active!

Wk	Lecture	Exercise	Other
1	Introduction to the course and background of mechatronics, Mechatronic design process	Learning / re-cap of Matlab	
2	Dynamic systems, frequency and time domain analysis	Laplace transform, Transfer function, Impulse and step responses, Basics of dynamic models	Preliminary exam deadline, release of project work
3	Electronics, control	Operational amplifier circuits, AD & DA conversion, Bode diagram	
4	Common control topologies, PID controller, Control applications	Common control topologies, PID controller, Control applications	Laboratory exercise 1
5	Mechatronic machine design with case example, Visiting lecturer	Mechatronic system simulation	
6	Summary of the course, Students' reflections: what we learnt, Mutual feedback	No exercises	Project work deadline
7	Project work wrap up /gala	Project work wrap up /gala	Course finished

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Learning goals this week

Operational amplifier circuits: non-inverting and inverting

AD & DA conversion: resolution quantization error

Filters, cut-off frequency, –3 dB frequency

Bode diagram

Second-order system transfer function

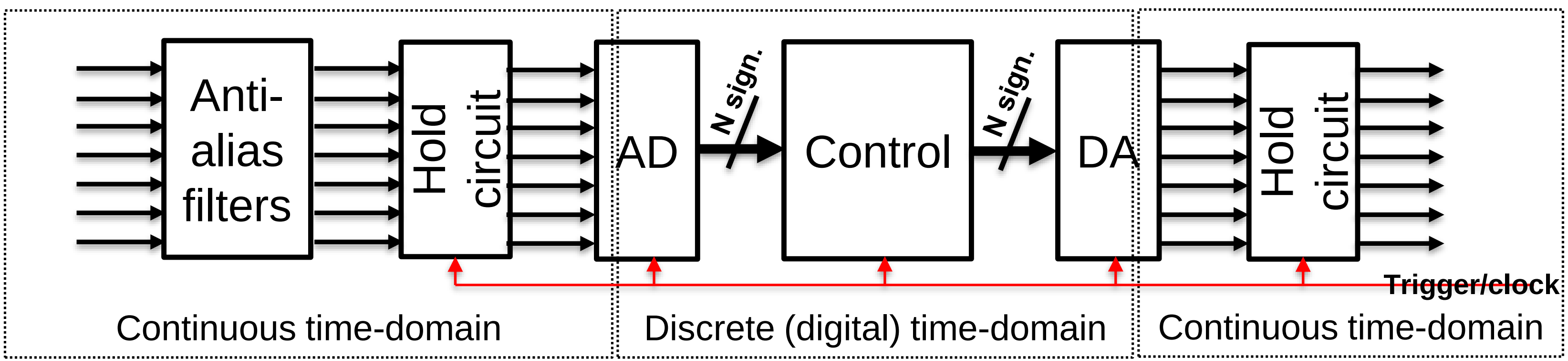
Analogue to digital (AD) & digital to analogues (DA) conversions

AD & DA conversion, background

Macro-physical quantities are mostly continuous (time, force, current, flow speed, …)

Modern control systems are mostly digital (discrete time, discrete quantities)

→ Mechatronic control systems require AD & DA conversions



AD & DA conversion, features

E.g: $101_2 = 1 \cdot 2^2 + 0 \cdot 2^1 + 1 \cdot 2^0 = 5_{10}$

Most significant bit (MSB): leftmost bit

Least significant bit (LSB): rightmost bit

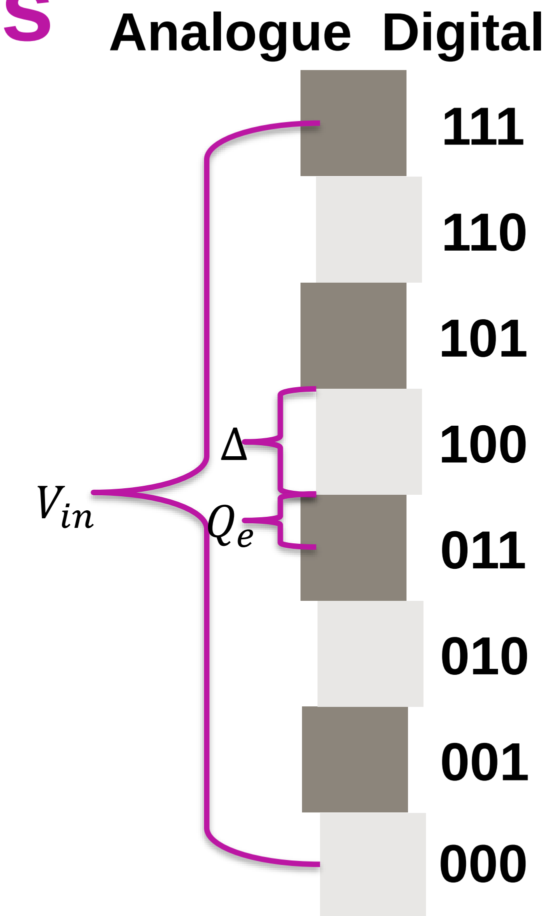
Delay proportional to sampling time T_s

Resolution, voltage range of one bit

$$\Delta = \frac{V_{in}}{2^N - 1}$$

Quantization error, voltage range of half bit

$$Q_e = \frac{\Delta}{2}$$



AD circuit example

V_{in}: **voltage to be converted**

***ABC*: binary number output**

Remember anti-alias filters before AD conversion (Shannon's sampling theorem)

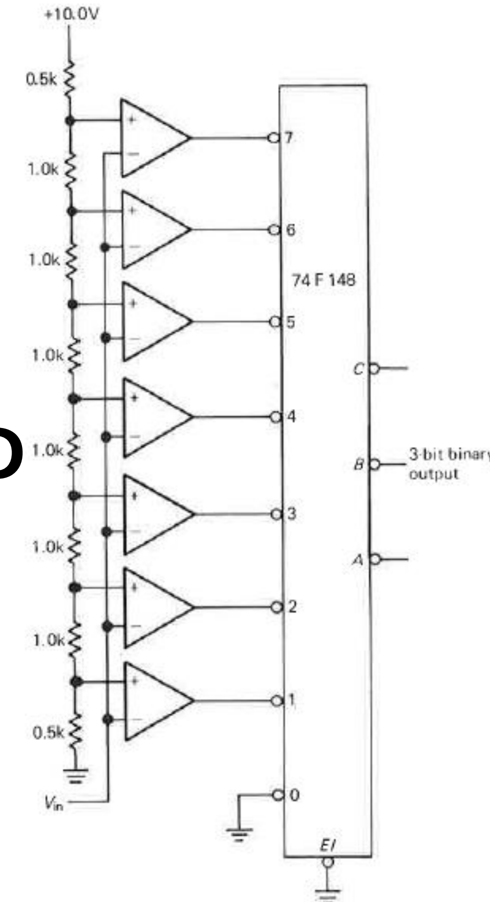


Figure 9.49. Parallel-encoded ("flash") A/D converter (ADC).

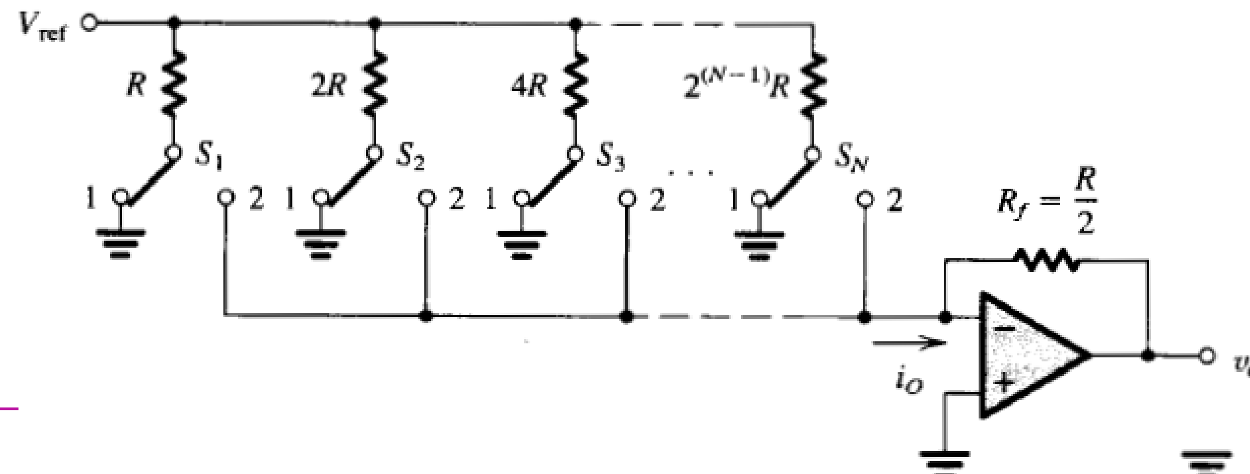
Pic. by Horowitz & Hill in "The art of electronics" on p. 621

DA circuit example

Digital number $S_1 \ldots S_N$ where S_N is least significant bit (LSB)

v_o: converted voltage output, V_{ref}: constant

Pic. by Sedra & Smith in "Microelectronic circuits" on p. 743



Operational amplifiers (op amps)

Basic principles of operational amplifiers (op amps)

Classical 741 op amp, pic by: https://electrosome.com/wp-content/uploads/2016/08/UA741-Opamp.jpg

Integrated circuit with tens of transistors

Active component

- Uses energy from external supply
- Output varies between $V_{min} < v_o < V_{max}$

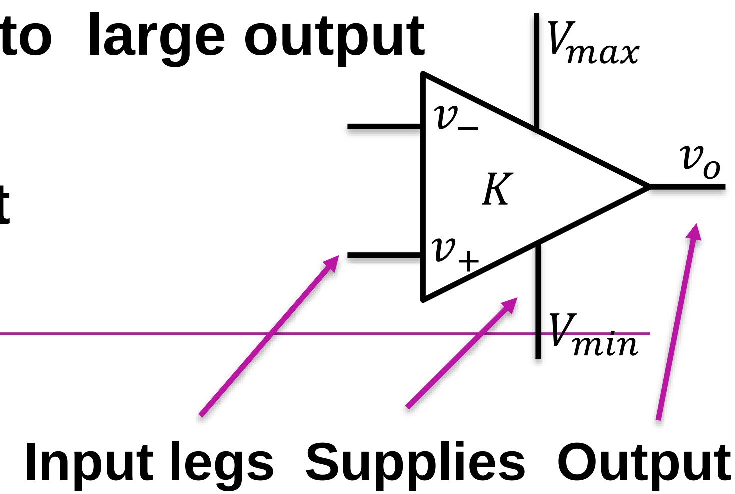
Gain extremely high $v_o = K(v_+ - v_-), K \gg 10000$

- Small difference in input legs leads to large output

Input impedance high

- Input legs draw insignificant current

Supplies not often drawn



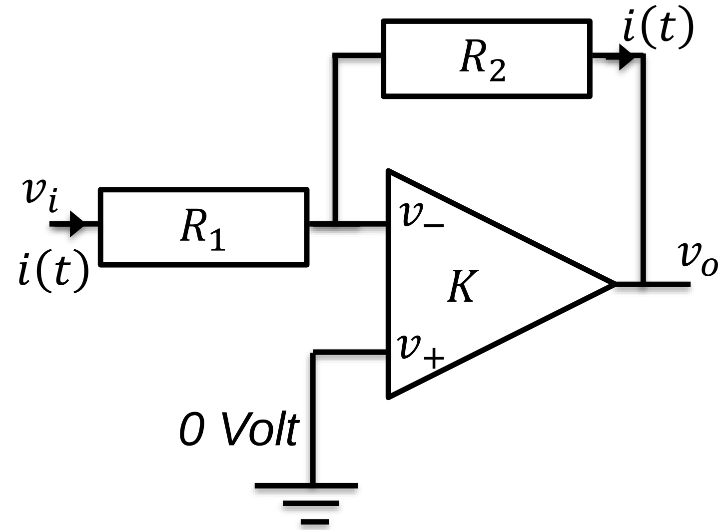
Op amp as inverting amplifier – closed-loop gain

Derive transfer function $\frac{v_o}{v_i}$

Use "virtual ground" $v_- = v_+ = 0\ V$

Input legs do not draw/emit current

Gain *K* is high



$$v_i = v_- - R_1 i$$
$$v_o = v_- + R_2 i$$
$$v_- = 0$$

$$\boxed{A_{cl} = v_o/v_i = -R_2/R_1}$$

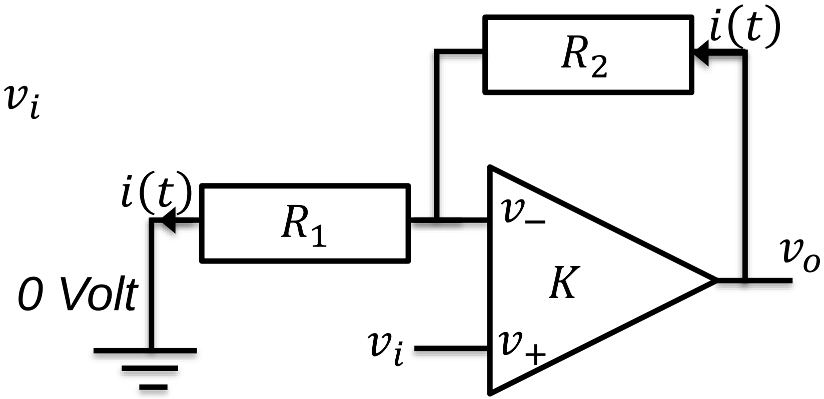
Op amp as non-inverting amplifier – closed-loop gain

Derive transfer function $\frac{v_o}{v_i}$

Use "virtual ground" $v_- = v_+ = v_i$

Input legs do not draw/emit current

Gain *K* is high



$$v_i = R_1 i$$
$$v_o = v_i + R_2 i$$
$$v_o = v_i + R_2 v_i / R_1$$
$$v_o R_1 = v_i (R_2 + R_1)$$

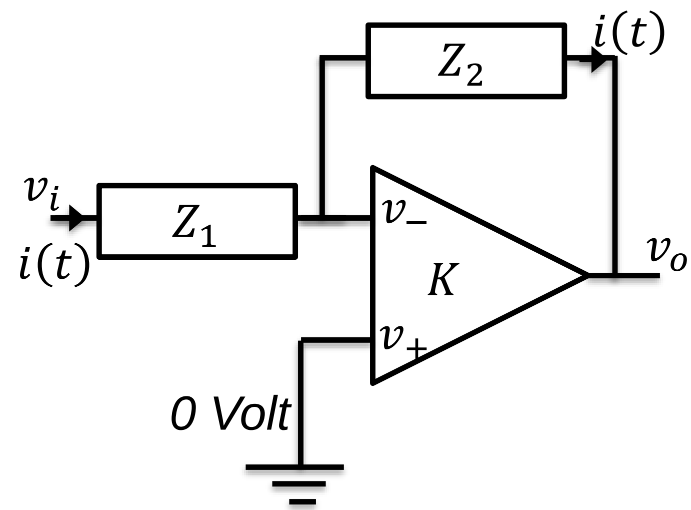
$$\boxed{A_{cl} = v_o / v_i = (R_1 + R_2)/R_1}$$

Op amps as filters and transfer function (Bode diagram) example

Inverting configuration closed-loop gains in case of impedances

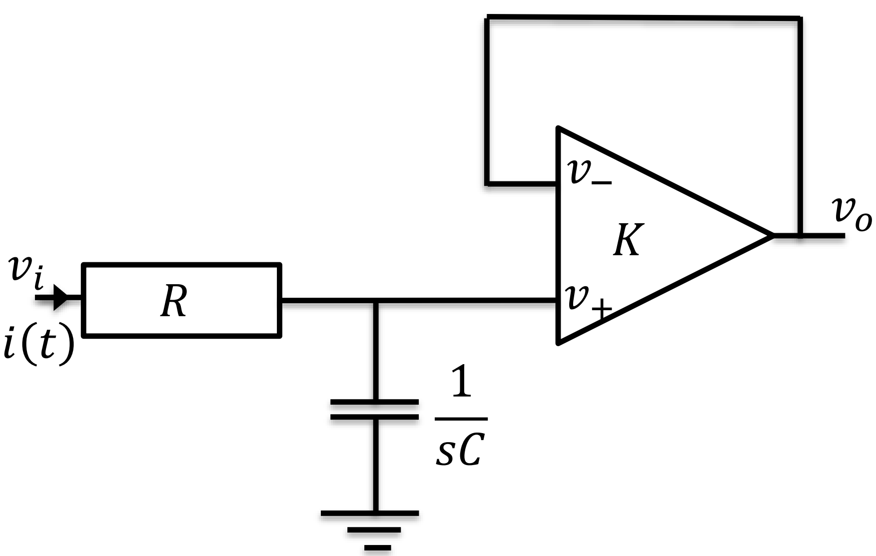
$$A_{cl} = v_o/v_i = -Z_2/Z_1$$

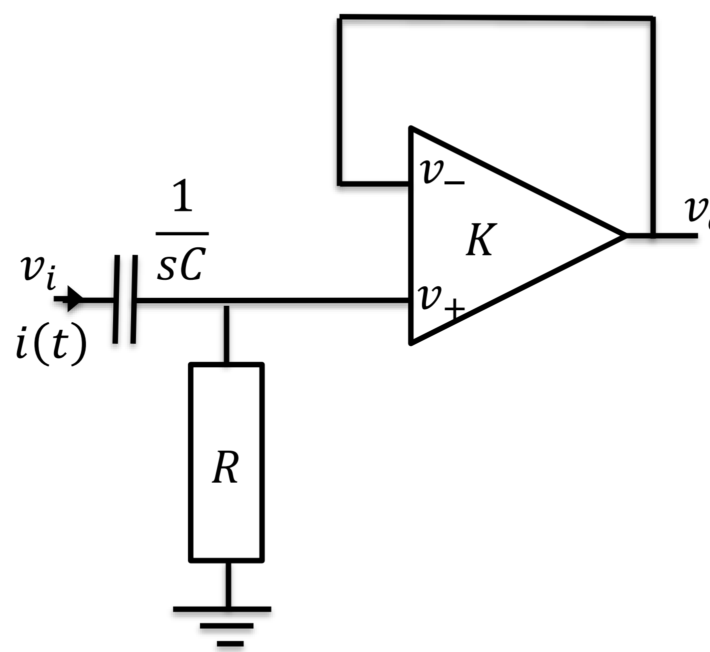
Z_1	Z_2	Filter type
R_1	R_2	Amplifier
$1/sC$	R_2	Derivative (HP filter)
R_1	$1/sC$	Integrator (LP filter)
sL	R_2	Integrator (LP filter)
R_1	sL	Derivative (HP filter)



HP: high-pass
LP: low-pass

Low-pass (LP) and high-pass (HP) filters





Analysis of transfer functions by using Bode diagrams

How to make manual Bode plot – analyse transfer function (1/4)

Analyse

- **Degrees of numerator and denominator** $D_{num} = \deg(num(s))$ $D_{den} = \deg(den(s))$
- **DC gain...** $s = \mathrm{j}\omega, \omega \to 0$
- **High frequency gain** $s = \mathrm{j}\omega, \omega \to \infty$
- **Corner frequencies (gain & phase change), solve** $num(s) = 0$ $den(s) = 0$

Corner frequencies: absolute values numerator and denominator roots

- **Numerator root (zero) increases gain 20 dB/decade**
- **Denominator root (pole) decreases gain 20 dB/decade**
- **Numerator root (zero) increases phase 90 degrees**
- **Denominator root (pole) decreases gain phase 90 degrees**

Note: roots (zeros and poles) are assumed stable (<0)

Note: corner frequency is close to –3 dB frequency ω_{-3dB}

How to make manual Bode plot – analyse transfer function (2/4)

Draw Bode plot gain on log-log (freq.-gain)

- **Start with DC gain** $s = \mathrm{j}\omega, \omega \to 0$
- **Go to first corner frequency, start to draw slope. Double pole or double zero means double slope**
- **Analyse & draw all poles & zeros, and check…………..** $s = \mathrm{j}\omega, \omega \to \infty$

Draw Bode plot phase on log-lin. (freq.-phase)

- **Start with DC phase, integrators or derivatives……….** $\frac{1}{s^N}$ or s^N
- **If integrators, derivative, DC phase not zero** $s^N\!: \varphi = N \cdot 90°$
- **Each pole advances phase 90 deg. Each zero lags phase 90 deg.**
- **Change starts decade before and ends decade after corner freq.**

Note: Slopes, gains, and phases are added up (simple summation)

How to make manual Bode plot – analyse transfer function (3/4)

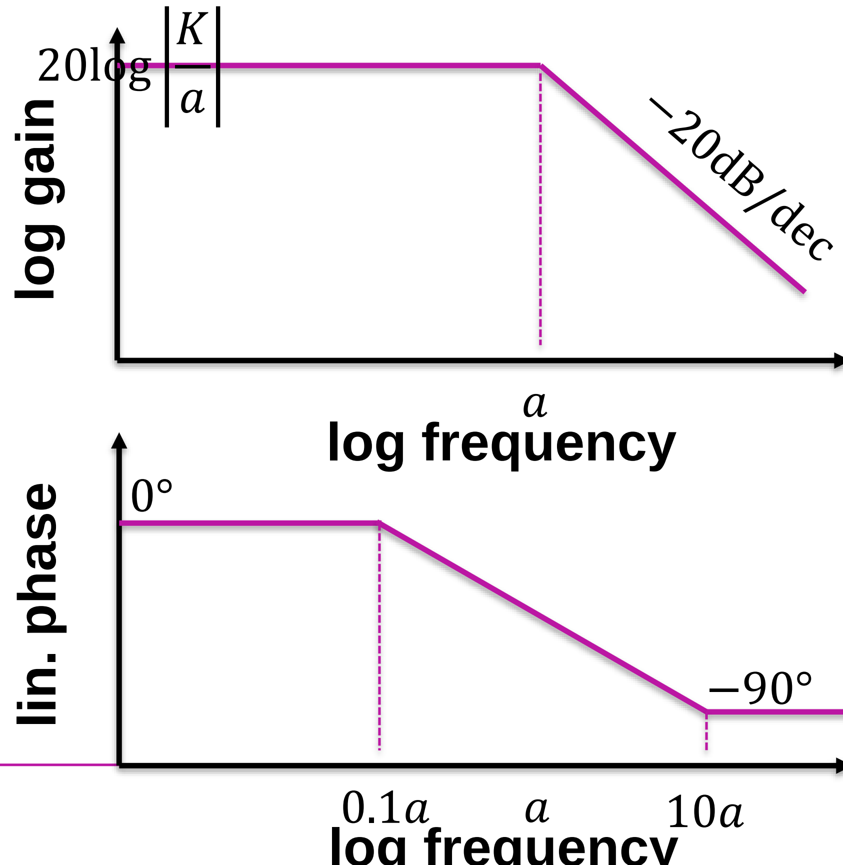
$$G_1(s) = \frac{K}{s+a}$$

Corner freq: a

$$G_1(\mathrm{j}\omega \to 0) = \frac{K}{a}$$

$$G_1(\mathrm{j}\omega \to \infty) = 0$$

$$G_1(\mathrm{j}\omega \gg a) \approx \frac{K}{\mathrm{j}\omega}$$



How to make manual Bode plot – analyse transfer function (4/4)

$$G_2(s) = \frac{sK\omega_0^2}{s^2 + 2\zeta\omega_0 s + \omega_0^2}$$

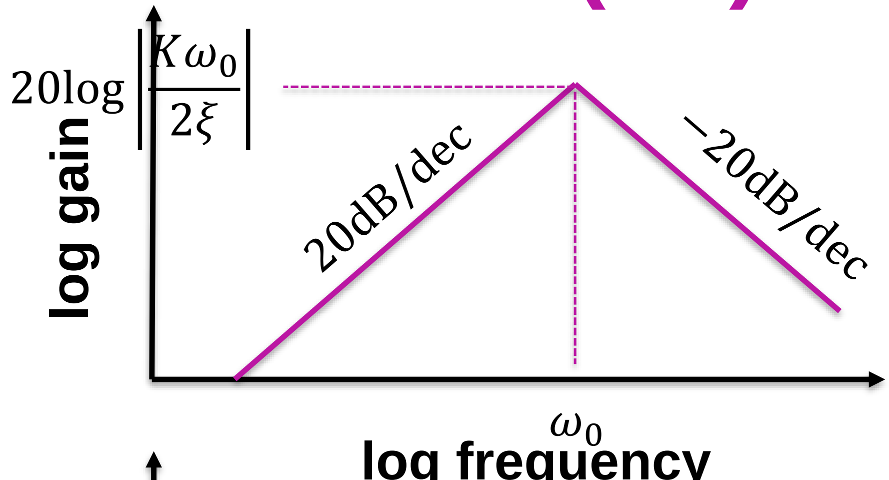
Corner freqs.: $0, \omega_0$

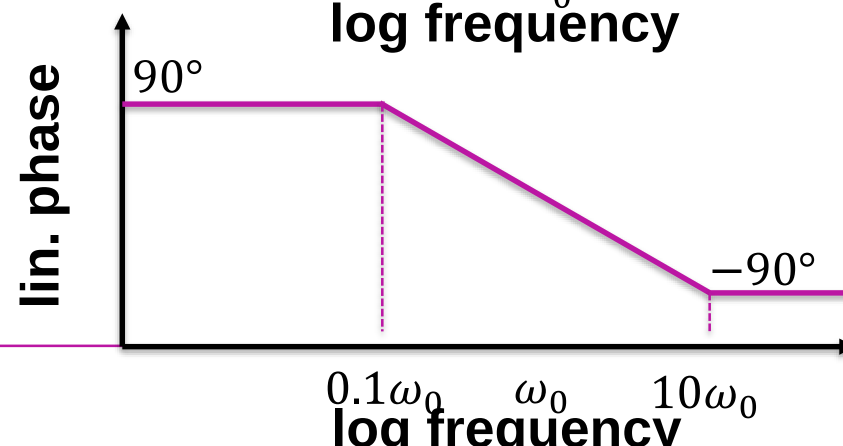
$$G_2(\mathrm{j}\omega \to 0) = 0$$

$$G_2(\mathrm{j}\omega_0) = \frac{K\omega_0}{2\xi}$$

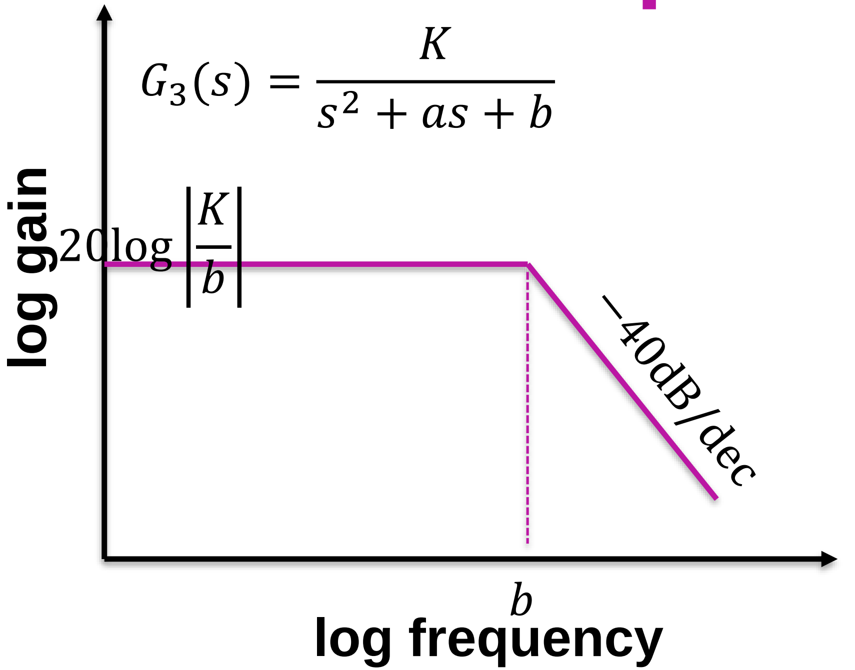
$$G_1(\mathrm{j}\omega \to \infty) = 0$$

$$G_1(\mathrm{j}\omega \gg \omega_0) \approx \frac{K}{\mathrm{j}\omega}$$

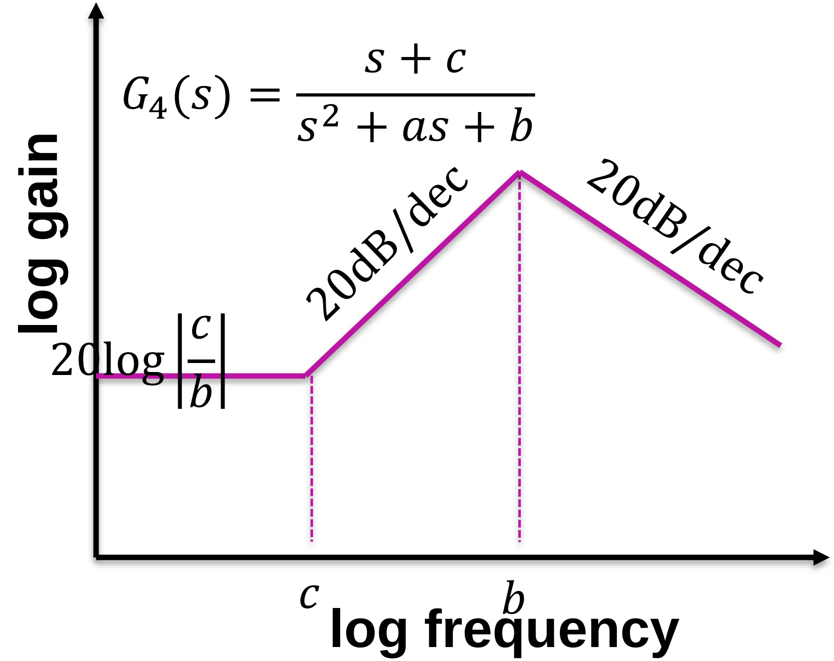




Manual Bode plots – extras



Phase: from zero to -180 deg. in range of 0.1*b* to 10*b*



Phase: from zero to +90 deg. and then to –90 deg.

Bode plot conclusions

Matlab has multiple tools to plot and analyse frequency responses, e.g: bode, bodeplot, freqresp, nichols, nyquist, spectrum

Q: Why to analyse manually?

A: To understand dynamic behaviour of system

Can you give examples of such dynamic systems?

decibels

dB – decibels

Logarithmic unit used to express ratio of two values of a physical quantity (wiki)

History: easy to express large ratios, easier to calculate (multiplication becomes summation, power becomes multiplication)

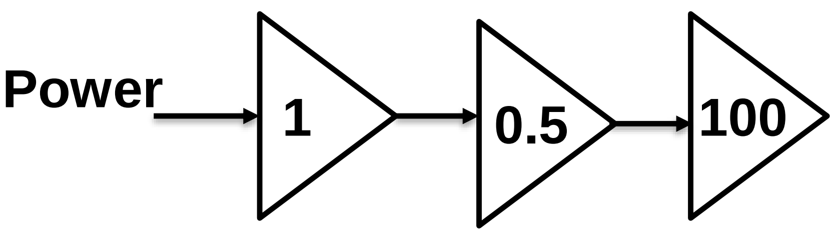
decibel volts: dBV (wiki)

Signal power amplification: $$10\log\left(\left(\left|\frac{v_o}{v_i}\right|\right)^2\right) = 20\log\left(\left|\frac{v_o}{v_i}\right|\right)$$

dB – decibels, calculation example

1) Signal amplitude has decreased from 1 to 0.5. How many dB:s is signal attenuated? How much has power been reduced?

2) Total gain of three filters below?



Gain 0.1: $10\log(0.1) = -10\ \mathrm{dB}$

Gain 0.5: $10\log(0.5) \approx -3\ \mathrm{dB}$

Gain 1: $10\log(1) = 0\ \mathrm{dB}$

Gain 5: $10\log(5) \approx 7\ \mathrm{dB}$

Gain 10: $10\log(10) = 10\ \mathrm{dB}$

Gain 100: $10\log(100) = 20\ \mathrm{dB}$

Group work (and lecture quiz)

Group work & lecture quiz 3

Discuss with your pair. Write down your answers and use them to answer lecture quiz today.

1. Draw manually Bode plot (gain and phase) of transfer function *X*(*s*)/*F*(*s*). Differential eq. (1 point): $m\ddot{x}(t) + c\dot{x}(t) + kx(t) = f(t)$

2. Design an integrator circuit by using two op amps circuits in series. The desired transfer function is 1/s. Draw the schematics and select the component sizes. (1 point).

3. Explain the circuit 74F148 used in the AD conversion example. What it takes as input, what is output, what is the purpose of the circuit in the given example (1 point)?