نظم القياس الإلكترونية
Electronic Measurement Systems (EMS)

كلية الهندسة الكهربائية والالكترونية – جامعة حلب
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المحاضرة 7 – القياسات التفاضلية والمترابطة

مصادر المحاضرة

- Electronic Instrumentation, Prof. Dr. Kofi Makinwa
  https://ocw.tudelft.nl/courses/electronic-instrumentation/
  - Lecture 4 - Differential Measurements and Respones of Amplifiers to common-mode signals
- Electronic Instrumentation, Prof. Dr. Kofi Makinwa
  https://ocw.tudelft.nl/courses/electronic-instrumentation/
  - Lecture 6 - Coherent detection

Introduction

- Differential (as opposed to single-ended) measurements have many advantages:
  - inherently reject common-mode interference and noise
  - allow a wider swing for a fixed power-supply voltage
  - minimize offset and even order distortion
  - (in some cases) lead to improved sensor linearity
- BUT most practical amplifiers also respond to some degree to common-mode signals
  - The appropriate figure of merit is the common-mode rejection ratio (CMRR).
  - Good amplifiers can achieve CMRRs > 120dB

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Differential Amplifiers

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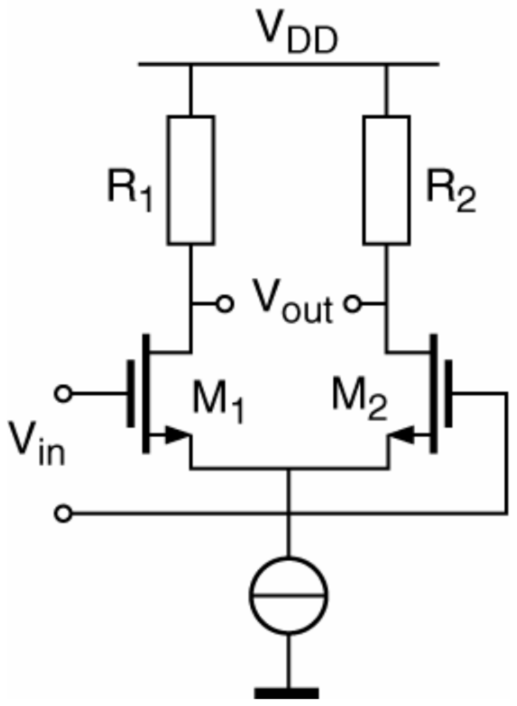
- Widely used to amplify DC signals

- Balanced structure is
- Nominally offset free
- Rejects common-mode and power supply interference
- Easily realized in both CMOS and bipolar technologies

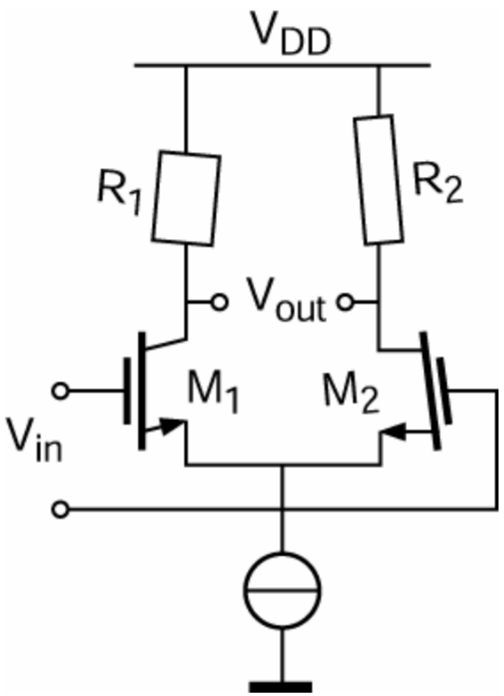


Practical Diff. Amps

- Component mismatch e.g. $R_1 \neq R_2$, $M_1 \neq M_2$ $\Rightarrow$ offset, finite CMRR & PSRR

- Mismatch is mainly due to
- Process variation
- Lithographic errors

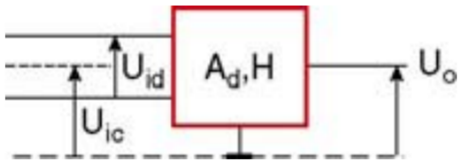
- All things being equal:
- CMOS amplifiers are 10x worse than Bipolar amplifiers



Common-mode rejection in differential measurements

A differential measurement is characterized by a (small) differential signal of interest, which is superimposed on a (large) common-mode signal.

The differential measurement should be sensitive to the differential signal only, regardless of the magnitude of the common-mode signal. The extent to which this is achieved by the read-out is by the common-mode rejection (*CMRR* or *H*).



$$H = \frac{A_d}{A_C} = \frac{\dfrac{U_o}{U_{id}}}{\dfrac{U_o}{U_{ic}}} = \left(\frac{U_{ic}}{U_{id}}\right)_{Uo=const}$$

Ideally: $U_o = A_d U_{id}$, but practically: $U_o = A_d(U_{id} + U_{ic}/H)$.

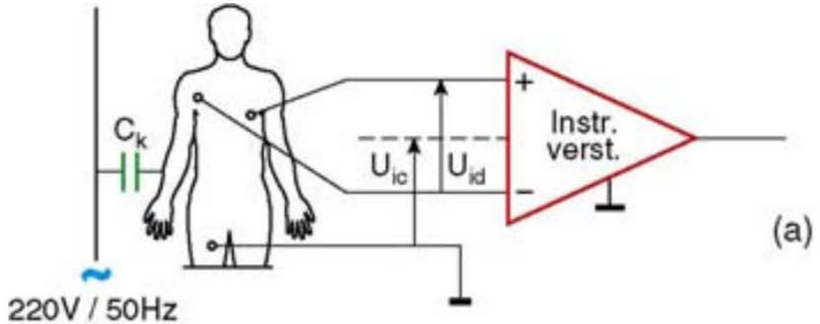
The term U_{ic}/H is an error signal, so H should be maximized.

Note: Reader uses "G_d" rather than "A_d"

ECG Readout

ECG
= small differential biopotential
$U_{id} \sim 10\ \mu V$ (0 - 100 Hz)

Superimposed on a large common-mode mains voltage
$U_{ic} \sim 1$ mV, 50 Hz.

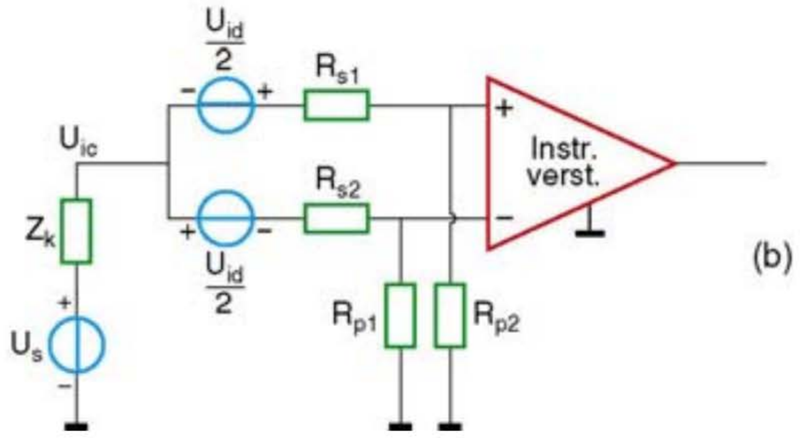


Application requires:

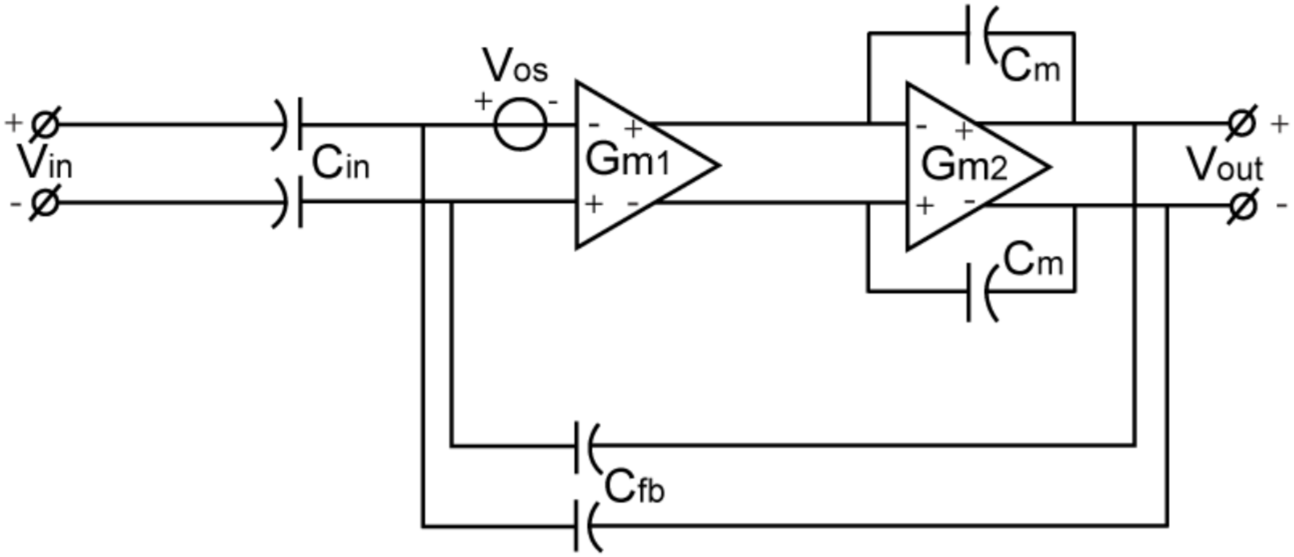
1. High CMRR > 80dB
(Filtering not possible)

2. High input impedance
(electrode impedances R_s are not well defined)

⇒ Instrumentation Amplifier

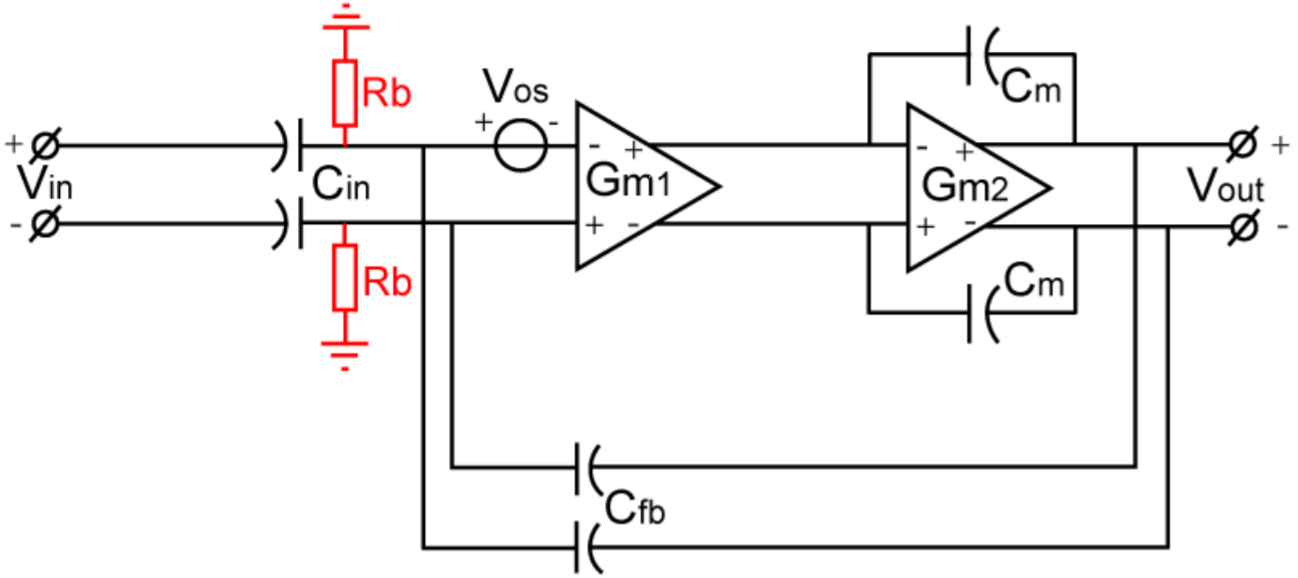


Achieving higher CMRR (1)



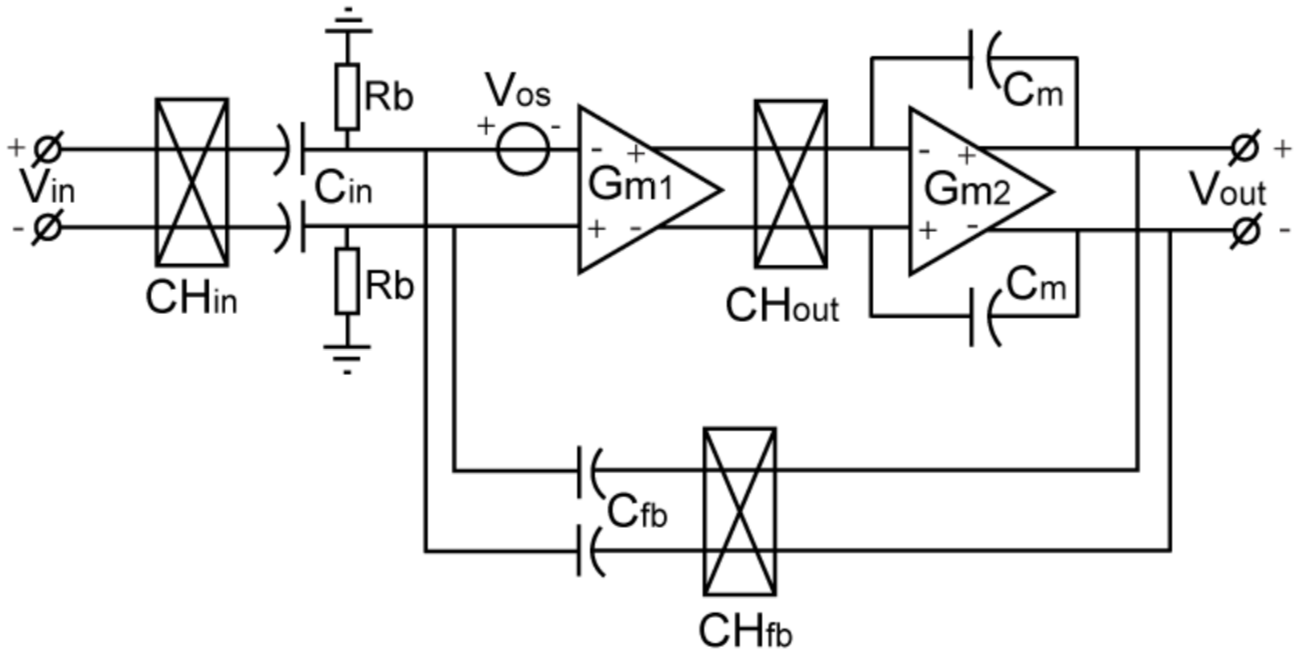
- Capacitors will block the common-mode voltage
  ⇒ a capacitively coupled amplifier? Closed-loop gain?
- Two stage amplifier ⇒ high open-loop DC gain (> 100dB)
- DC stability?

Achieving higher CMRR (2)



- Extra resistors are needed to establish DC voltages
- Trade-off: should be quite large (MΩ) to minimize noise, should be small to minimize CM settling time
- DC closed-loop gain?

Achieving higher CMRR (3)



- Polarity reversing switches (known as choppers) convert input DC signals into AC signals (square-waves)
- To maintain feedback polarity, the feedback path and the amplifier also contain choppers

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Achieving higher CMRR (4)

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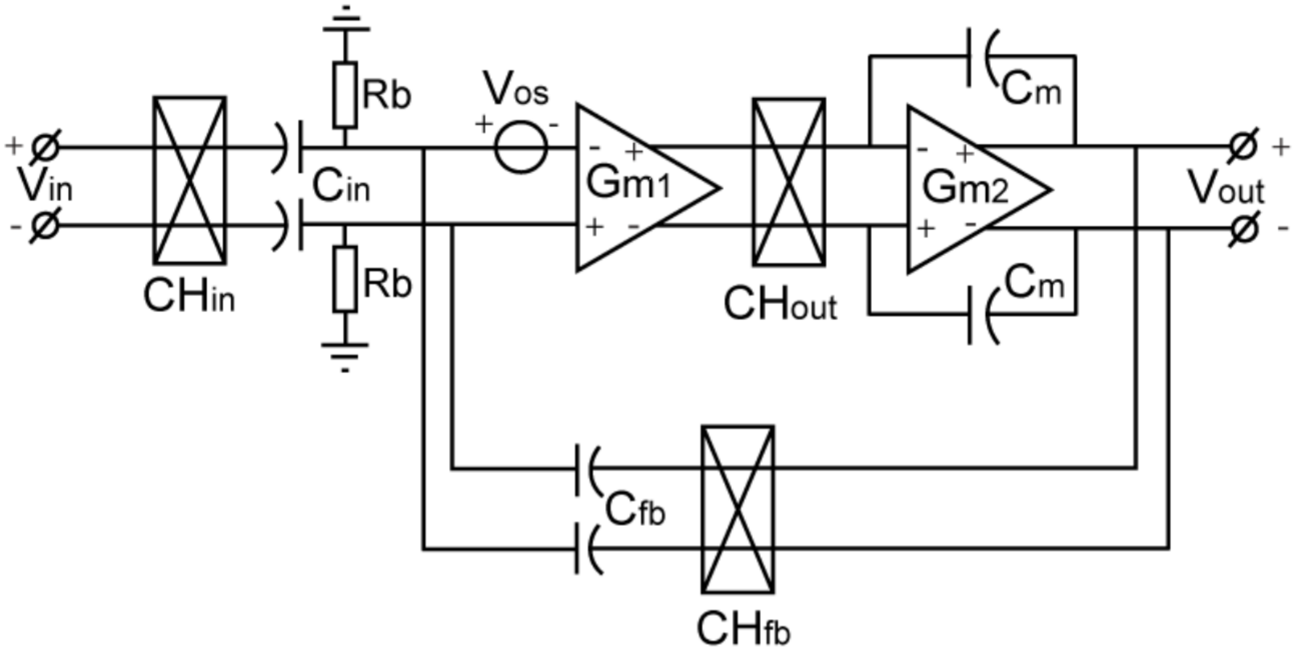


- Result: 1μV offset, 0.16% gain error, 134dB CMRR, 120dB PSRR

Q. Fan, F. Sebastiano, J.H. Huijsing and K.A.A. Makinwa, “A 1.8μW 1μV-Offset Capacitively-Coupled Chopper Instrumentation Amplifier in 65nm CMOS,” *J. Solid-State Circuits,* vol. 46, is. 7, pp. 1534 - 1543, July 2011.

PSRR

- A close cousin of CMRR is the power-supply rejection ratio (PSRR), which expresses how sensitive the amplifier is to changes in its supply voltage.

$$PSRR = \frac{A_d}{A_{sy}} = \frac{\dfrac{U_o}{U_{id}}}{\dfrac{U_o}{\Delta U_{sy}}} = \left(\frac{\Delta U_{sy}}{U_{id}}\right)_{Uo=const}$$

- Here ΔU_{sy} represents the changes in the supply voltage
- A good instrumentation amplifier will have a PSRR > 100dB

Introduction

- Synonyms: coherent detection, synchronous demodulation, lock-in amplification, chopping??
- These are all modulation techniques that are used to improve the low frequency performance of measurement systems
- When square-wave modulation is employed, the technique is referred to as <u>chopping</u>

Coherent detection

When to use it?

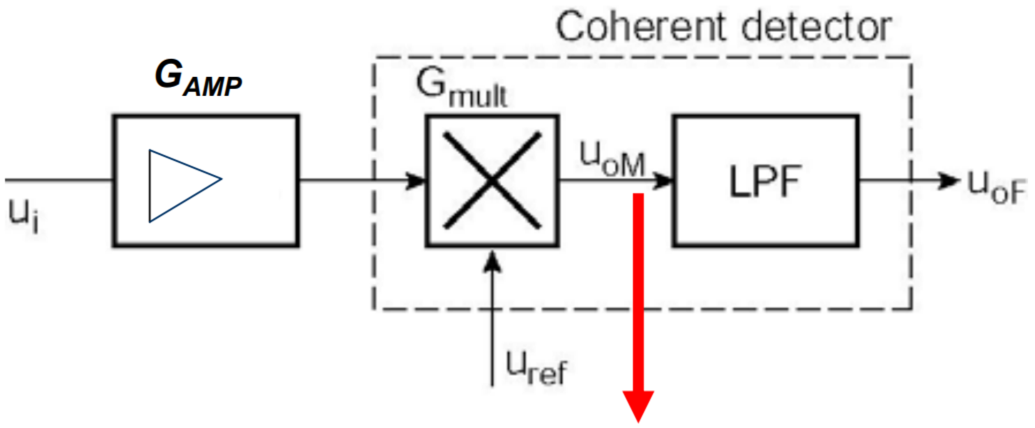
- When measuring low-bandwidth or quasi-static signals in the presence of high noise or disturbance levels.
- If a high dynamic range is required

Therefore it is often used to readout sensors e.g.

- (MEMS) Accelerometers (fF capacitance changes)
- Optical (infrared) detectors (fA's of current)
- Magnetic sensors (mV's)
- Strain gauges (mV's)

A coherent detector behaves like a bandpass filter

Time domain analysis



$$u_{oM} = G_{Amp} G_{mult} \left[\hat{u}_i \sin(\omega_i t) \hat{u}_r \sin(\omega_r t) \right]$$

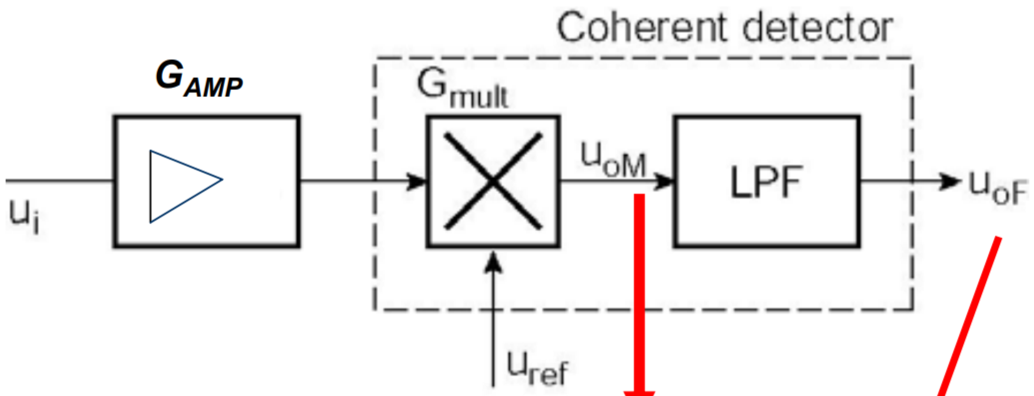
$$u_{oM} = G_{Amp} G_{mult} \frac{\hat{u}_r \hat{u}_i}{2} \left[\cos((\omega_r - \omega_i) t) - \cos((\omega_r + \omega_i) t) \right]$$

Now if: $\omega_r = \omega_i$ (Coherent signals !) then:

DC

$$u_{oM} = G_{Amp} G_{mult} \frac{\hat{u}_r \hat{u}_i}{2} \left[1 - \cos(2\omega_i t) \right]$$

Amplitude detection



$$u_{oM} = G_{Amp} G_{mult} \frac{\hat{u}_r \hat{u}_i}{2} \left[1 - \cos\left(2\omega_i t \right) \right]$$

$\omega_r = \omega_i$

The low-pass filter removes the second harmonic:

$$u_{oF} = G_{LPF} G_{Amp} G_{mult} \frac{\hat{u}_r \hat{u}_i}{2}$$

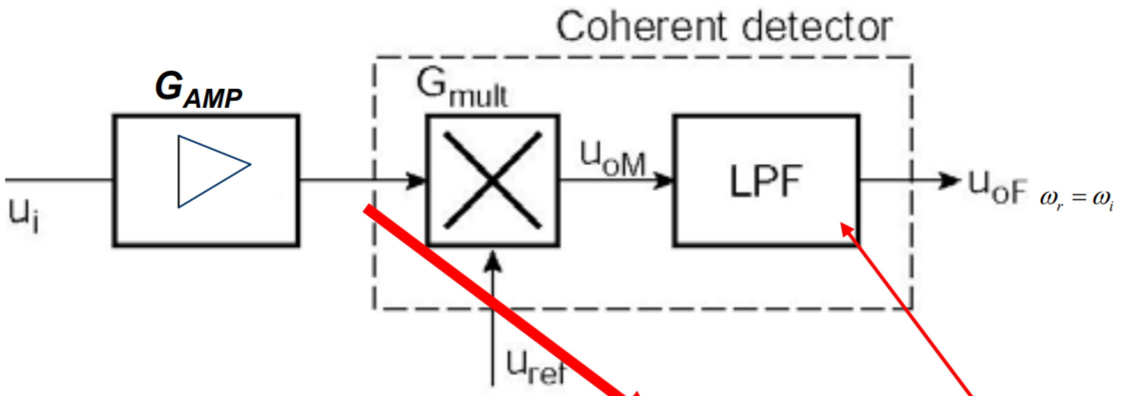
This coherent detector detects the **amplitude** of the input signal.

Note that in this case $\mathbf{U_i}$ **and** $\mathbf{U_{ref}}$ are in-phase (Synchronous detection).

What if they are not in-phase ????

Phase detection

Suppose U_i and U_{ref} have a phase difference:



$$u_{oM} = G_{Amp}G_{mult}\left[\hat{u}_i \sin\left(\omega_i t+\varphi\right)\hat{u}_r \sin\left(\omega_r t\right)\right]$$

$$u_{oM} = G_{Amp}G_{mult}\frac{\hat{u}_r\hat{u}_i}{2}\left[\cos\left(\left(\omega_r-\omega_i\right)t+\varphi\right)-\cancel{\cos\left(\left(\omega_r+\omega_i\right)t+\varphi\right)}\right]$$

$$u_{oF} = G_{LPF}G_{Amp}G_{mult}\frac{\hat{u}_r\hat{u}_i}{2}[\cos\left(\varphi\right)]$$

=0

This coherent detector is also **phase sensitive**.

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Coherent detection in practice

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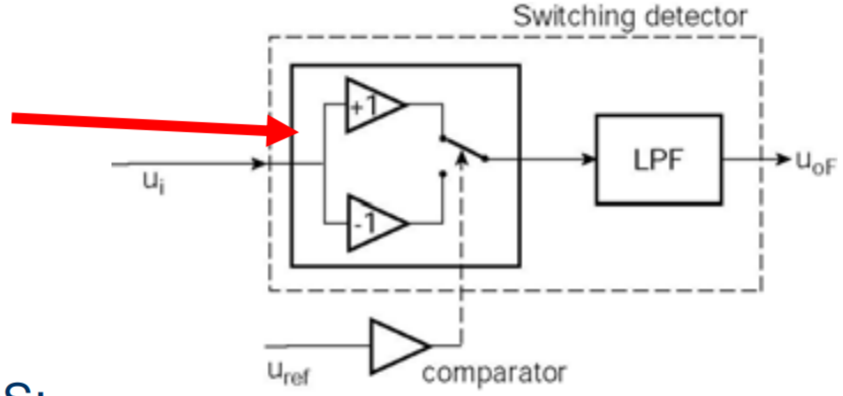
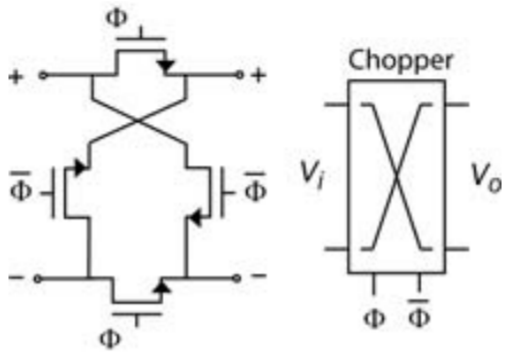
Linear operation of an analog multiplier circuit, working over a large range of input signals is difficult to realize in practice.

A much simpler realization is a switching detector a.k.a. a **chopper**



Chopper realization in CMOS:

Easy: just 4 transistors!
Accurate: does not introduce offset
But: switching spikes can cause problems (residual offset)



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Summary

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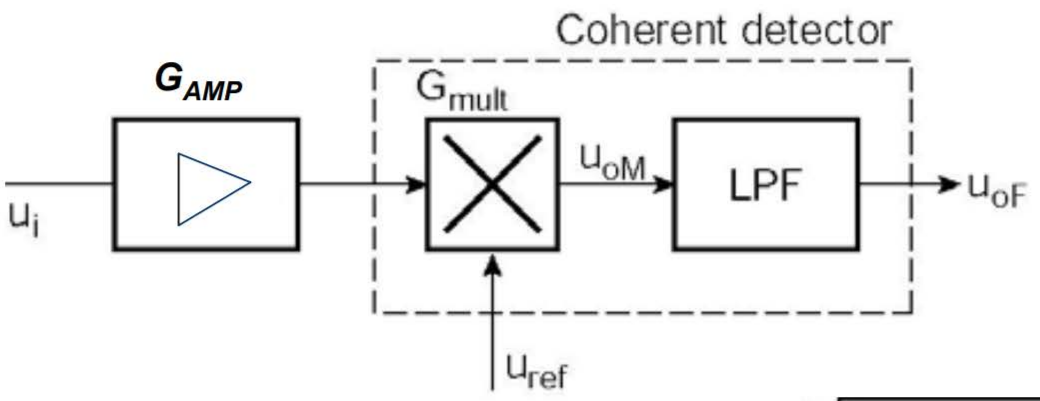
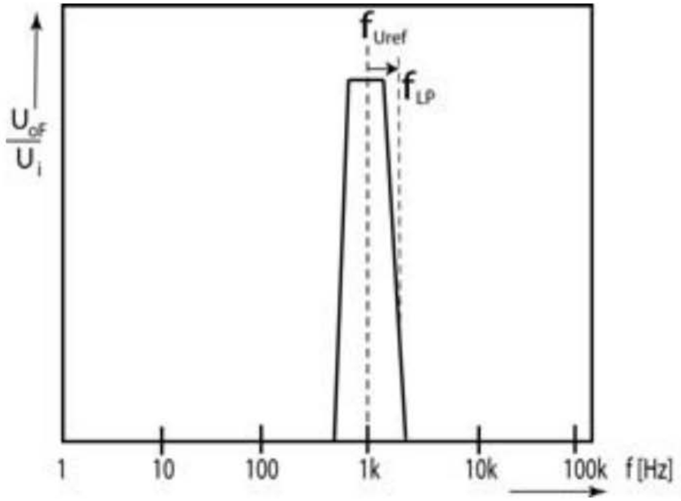


REMEMBER:

- **An ideal coherent detector is only sensitive to frequency components in a narrow band around a reference signal U_{ref}.**
- **The low-pass filter determines the signal bandwidth**



So what happens if U_{ref} is a square wave ??

DEMO: Coherent detection for the readout of strain-gauges

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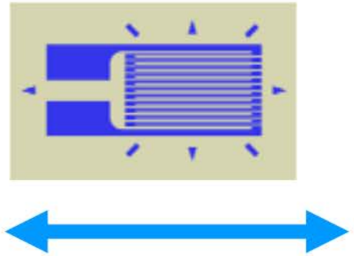

R is typically 100-2000 Ω

ΔR is typically 10^{-1} - 10^{-5} Ω

Very small changes in resistance should be measured

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DEMO: Wheatstone bridge with strain gauges

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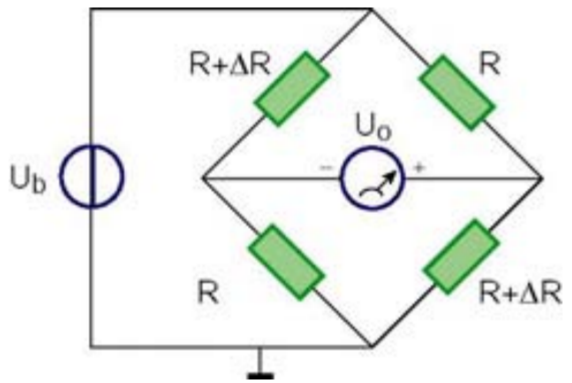
Wheatstone ½ bridge

Construction enables only stressed and non-stressed strain gauges



$$U_{o+} = \frac{R+\Delta R}{(R+\Delta R)+R} U_b = \frac{R+\Delta R}{2R+\Delta R} U_b$$

$$U_{o-} = \frac{R}{(R+\Delta R)+R} U_b = \frac{R}{2R+\Delta R} U_b$$

$$U_d = U_{o+} - U_{o-} = \frac{\Delta R}{2R+\Delta R} U_b$$

Non-linearity error is small if $\Delta R << 2R$

U_b can be an AC source of well-known frequency
U_o is a very small AC signal (typically a few uV)

with a high noise level !

DEMO: Coherent detection for the readout of strain-gauges

Some data:

Strain gauges : 120 ohm, length 6mm

Steel bar: area = 1cm^2

1 kg gives: Δl =2,86 nm

Resistance change: ΔR = 120 $\mu\Omega$

Relative change: $\Delta R/R = 10^{-6}$

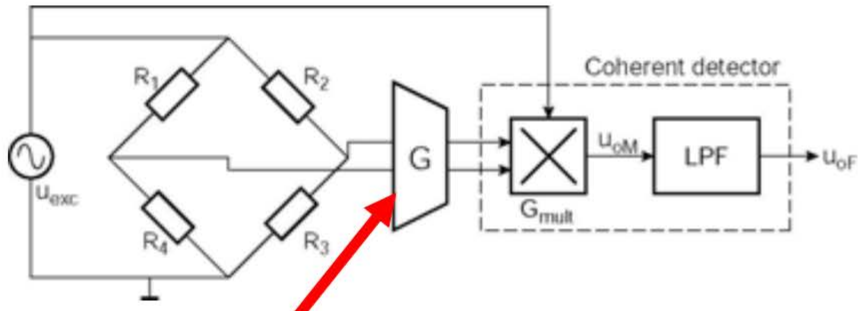
Noise level:

Force: 10N , or 1kg

Max force: 15 kN, or 1500 kg (Steel bar limit)

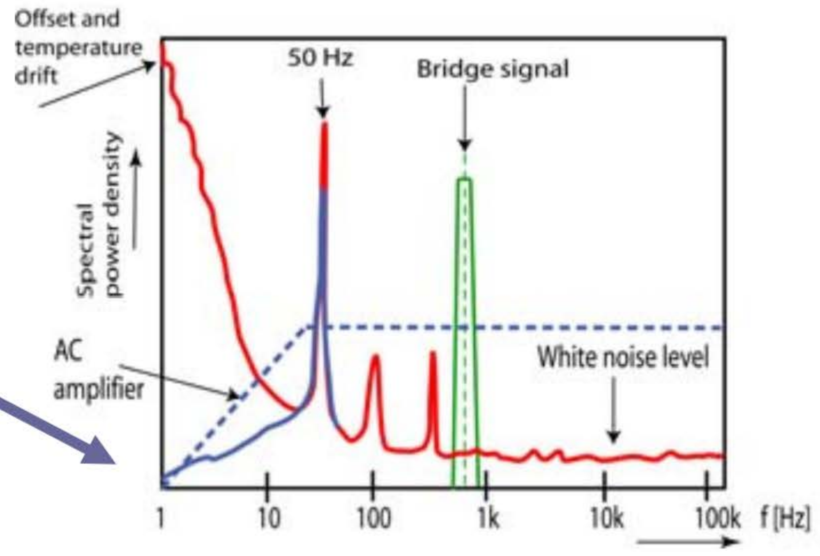
Dynamic range: 1500/0.1 = 15*10^3 = 84 dB

Increasing the dynamic range



Use an AC amplifier

Offset suppression reduces overload on multiplier



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Detection limits

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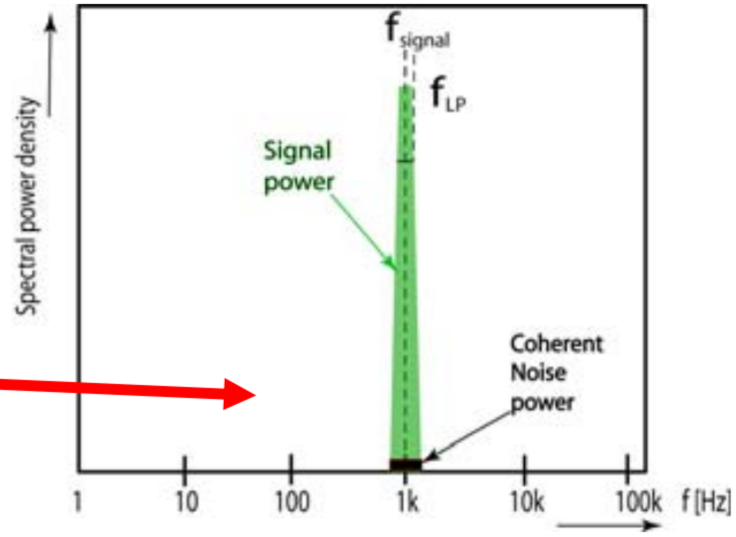
Signal-Noise ratio

=

$$\frac{\textbf{Green area}}{\textbf{Black area}}$$

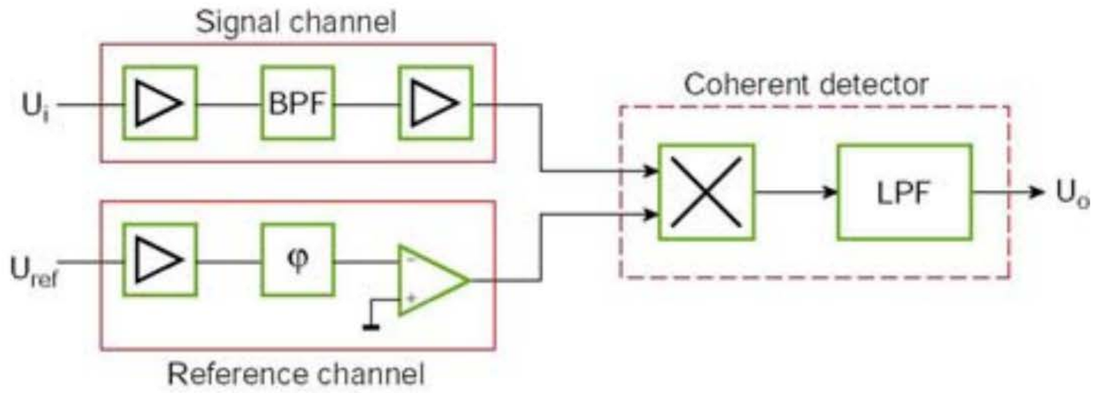


Other detection limits are due to:

- o Offsets in both input- and output channel
- o Non-linearities in the reference channel
- o Non-linearities in the input channel
- o Non-linearities at the output of the multiplier

Lock-in amplifier

A lock-in amplifier is a coherent detector with all the extra features required of a general-purpose laboratory instrument.



DEMO: Coherent detection in an optical system

Source: LED modulated with a sine wave

Detector: Photodiode

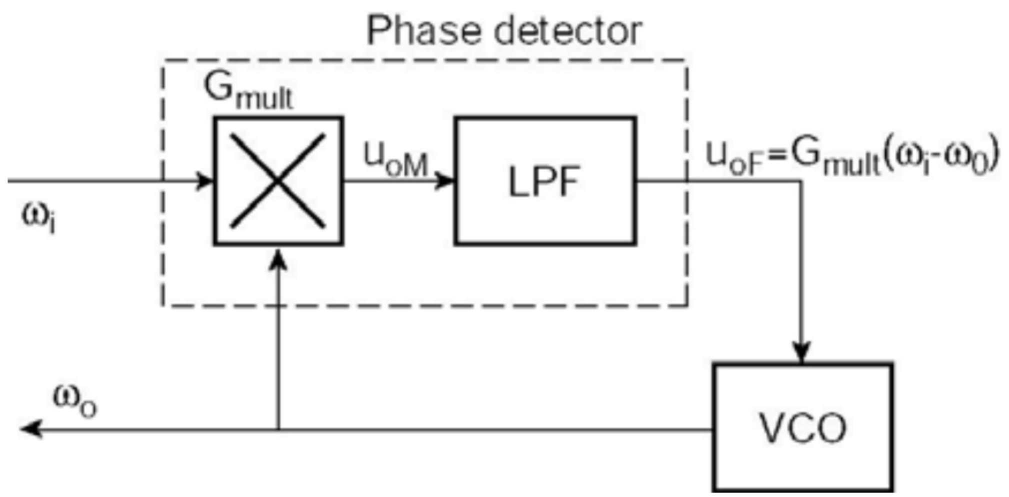
Instrument: Analog lock-in amplifier (PAR 186)

Interference:

Ambient light, DC (offset), 50 Hz mains (lamp)

PLL for recovery of excitation voltage

The excitation frequency of remote sensors is not always directly available, but can be retrieved from the sensor's output signal by a phase-locked loop (PLL).



The loop drives the VCO so as to minimize the error signal U_{oM}

As a result, $\omega_i \sim \omega_o$ with a small loop-gain-dependent phase error

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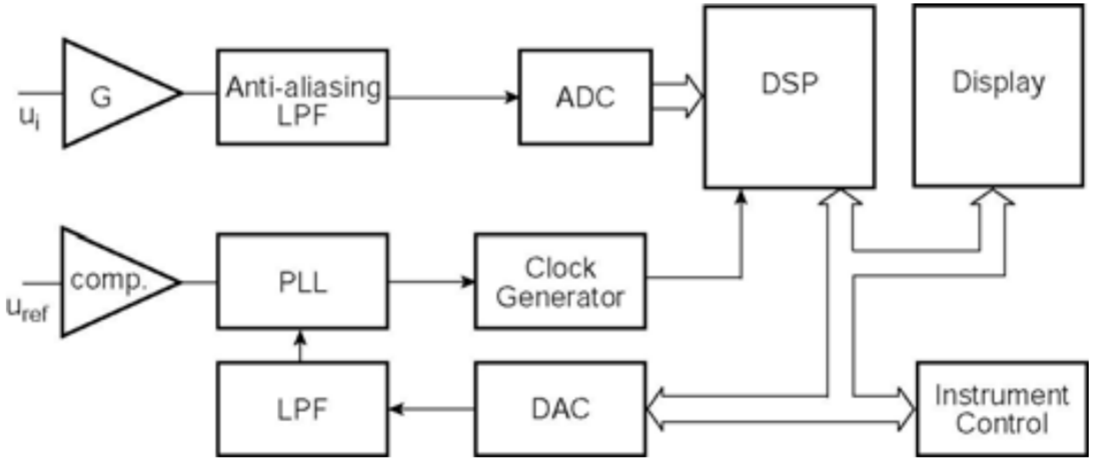
Digital lock-in amplifier

Analog functionality is replaced by digital signal processing (DSP)

⇒ Cost, Flexibility, User friendliness



ADC and DSP are critical (frequency limiting) components

Digital lock-in amplifiers are becoming more and more economical and common in test-setups in the lab and in industry

Summary

Coherent detection is a powerful technique to accurately measure low-level periodic signals in the presence of high levels of noise and interference.

Both amplitude and phase can be measured

The signal frequency should be known (reference channel) or it should be possible to regenerate it with a PLL.

The operating frequency should be in a frequency band where disturbing signals and noise are low.

Distortion in the input- or reference channel can lead to harmonic sensitivity

Modern (digital) lock-in amplifiers can also measure the amplitude and phase of harmonic signals (2f, 3f ,4f etc.)
e.g. for the measurement of signal distortion.