Tutorial:
Phase-Locked Loops & Quartz Crystal Oscillators

Dominik Schneuwly

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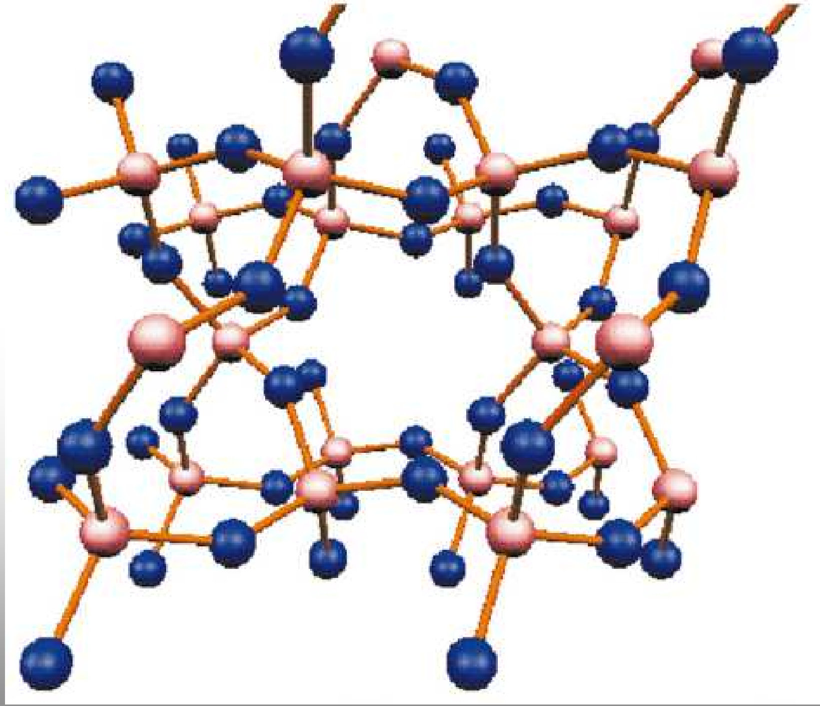
1. Quartz Crystal Oscillator (XO) Technology

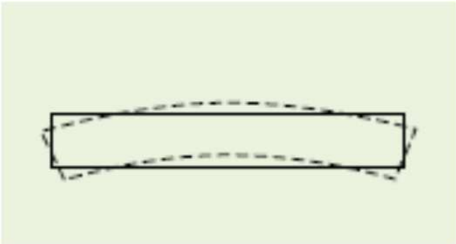
Quartz Crystal

Quartz = SiO_2

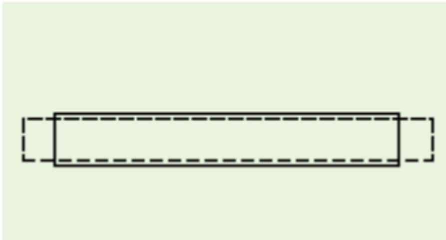
Pink = silicon atoms
Blue = oxygen atoms



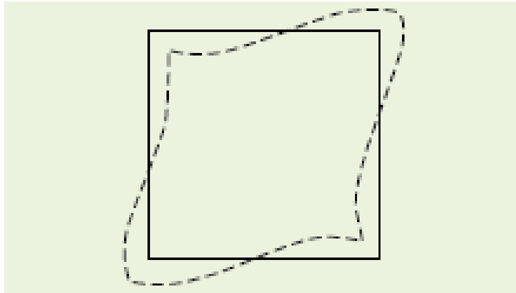
Vibration Modes, Resonance Frequency, High Q



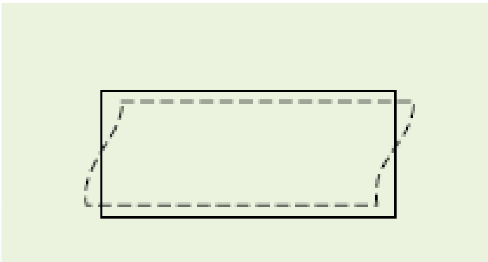
Flexure Mode



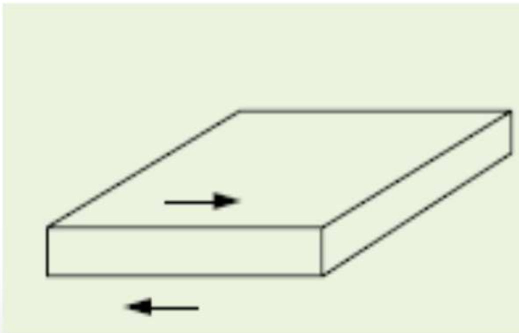
Extensional Mode



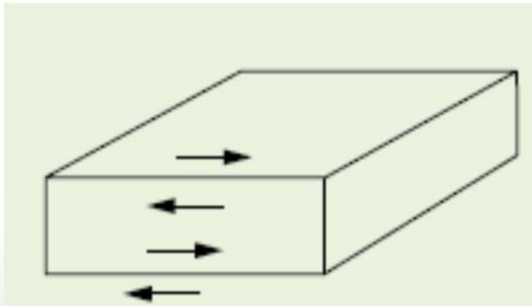
Face Shear Mode



Thickness Shear Mode



Fundamental Mode Thickness Shear

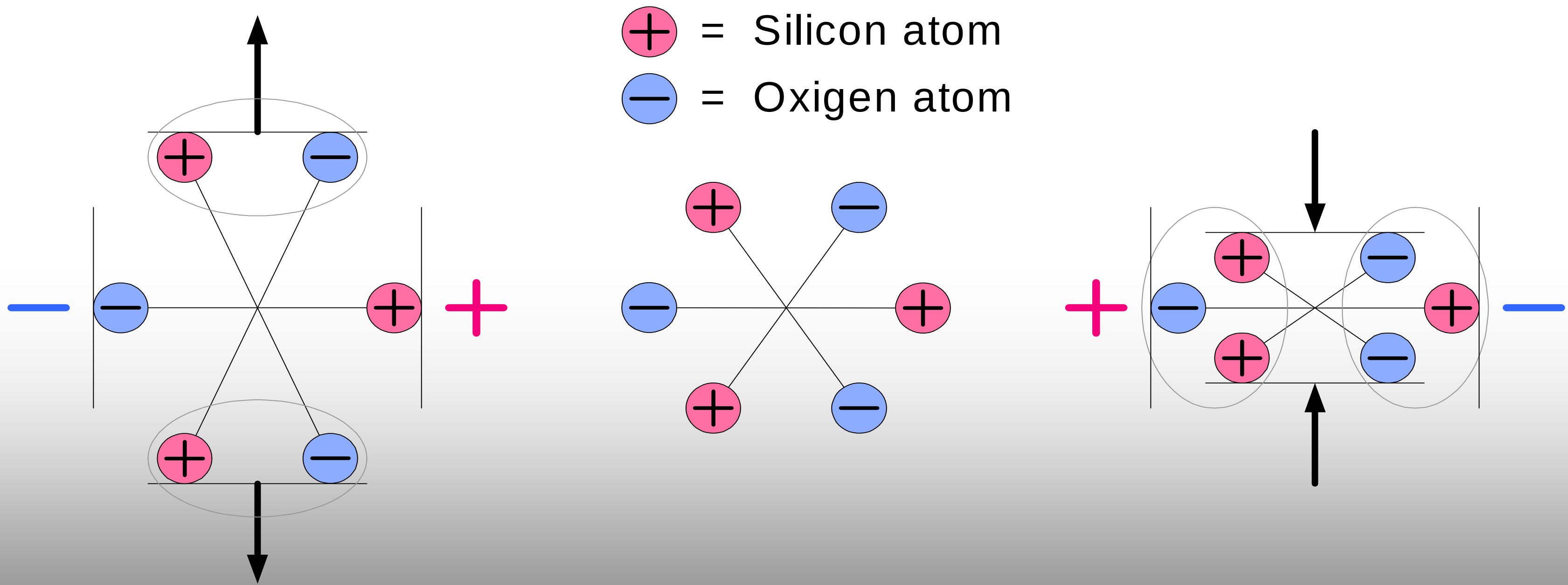


Third Overtone Thickness Shear

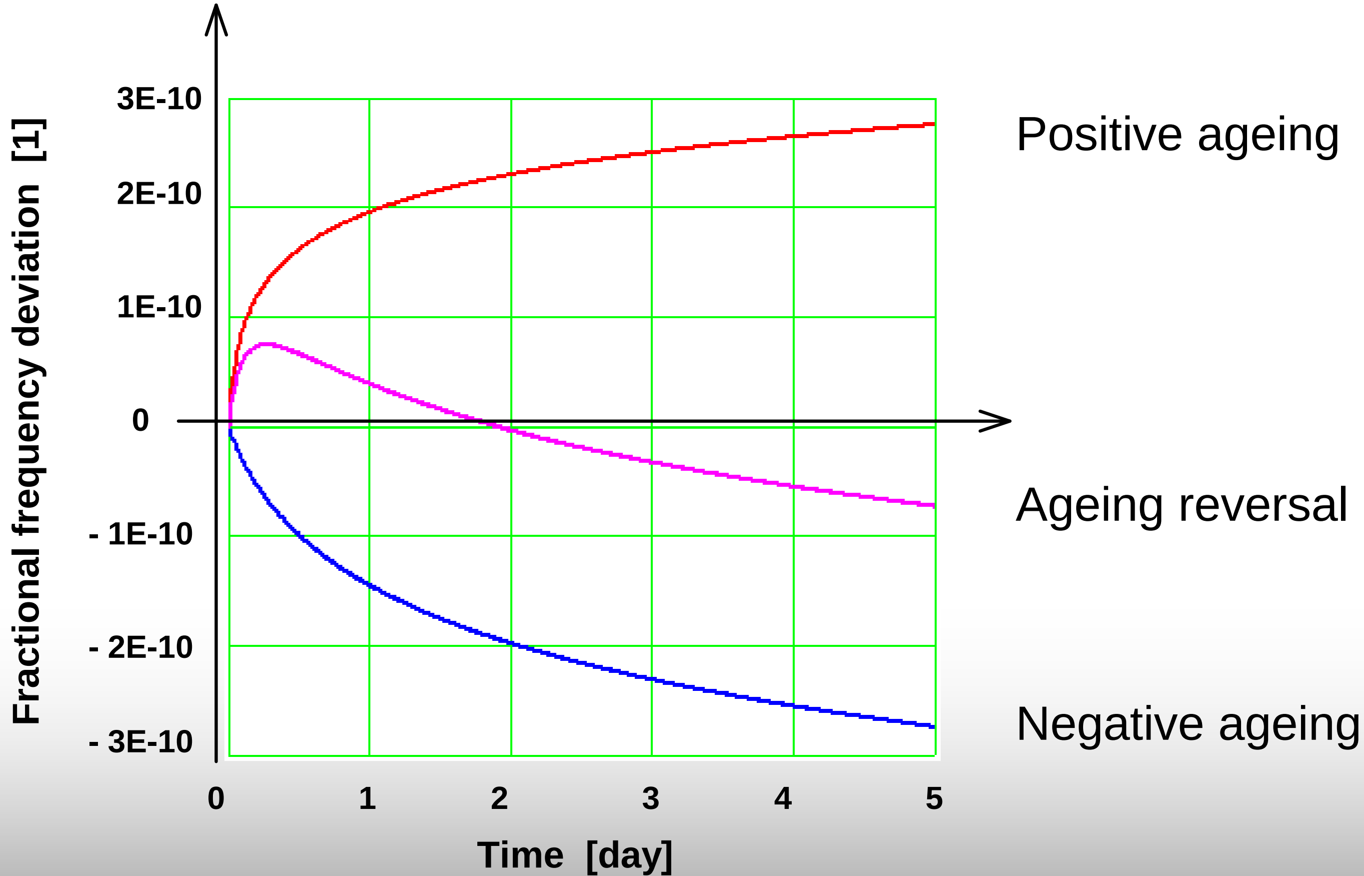
Piezo-electric Effect

Piezo-electric effect:

- Mechanical strain ⇒ voltage
- Voltage ⇒ mechanical deformation



Frequency Drift Due to Ageing



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Frequency vs. Temperature

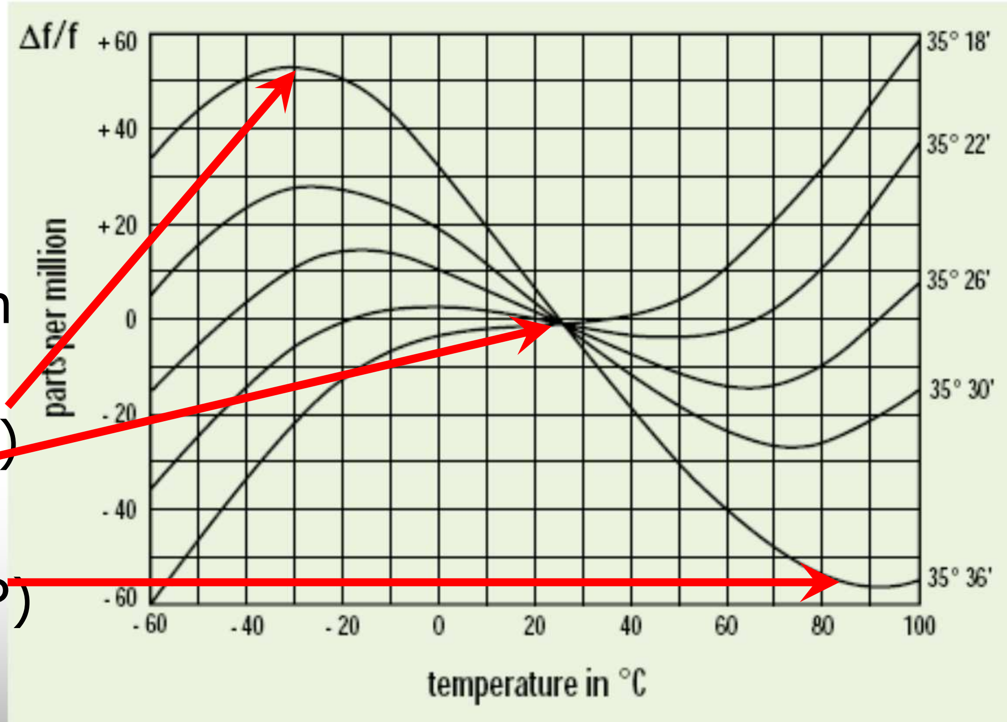
SC-cut:

- Θ = 34°
- Φ = 22°

Δf/f as a function of temperature

(parameter: *ΔΘ* = deviation from reference angle)

- Lower Turnover Point (LTP)
- Inflection Point (IP)
- Upper Turnover Point (UTP)



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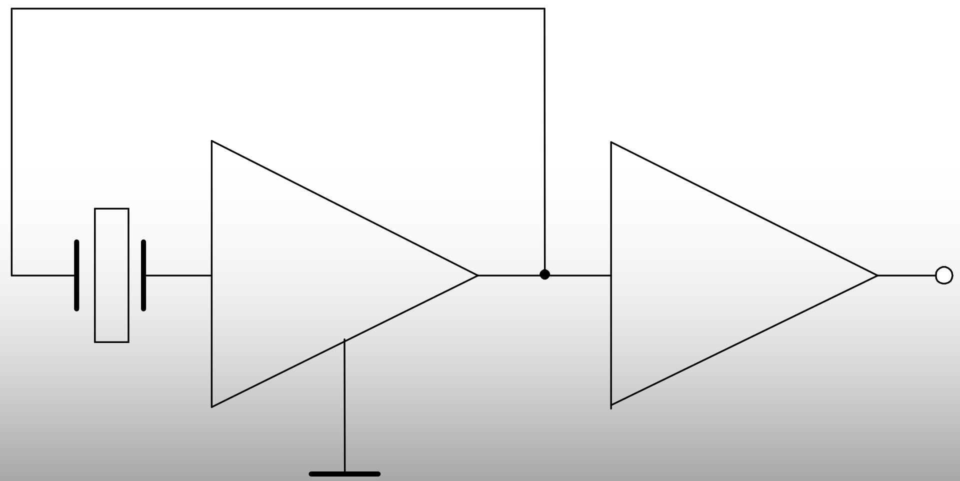
XO Categories rel. Temp. Control

XO, Crystal Oscillator:

- LTP centered in the operation temperature range
- > 1E-7 / °C



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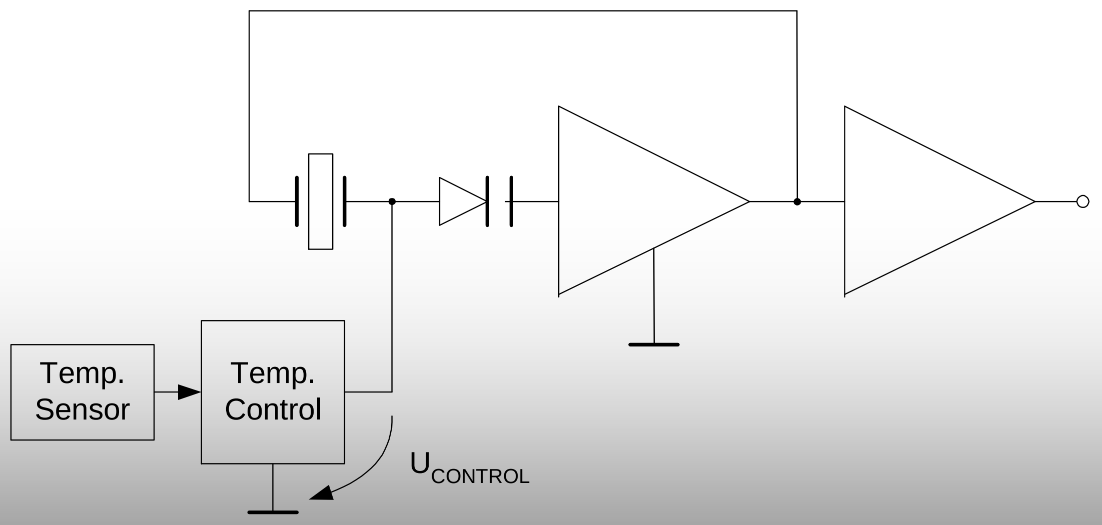
XO Categories rel. Temp. Control

TCXO, Temperature Compensated XO:

- Resonance frequency is modified by a varactor diode so as to compensate temperature sensitivity
- 5E-8 to 5E-7 over [-55°C to 85°C]



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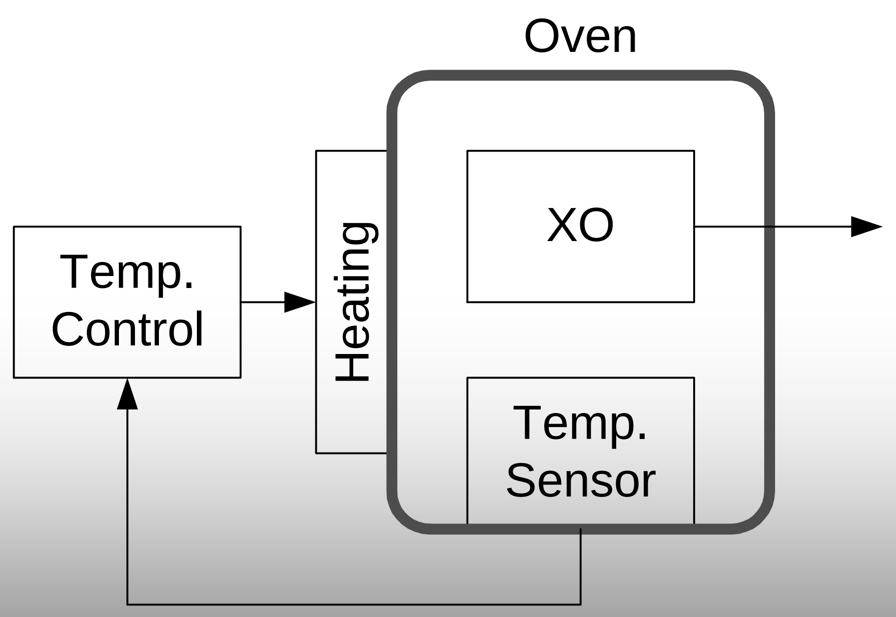
XO Categories rel. Temp. Control

OCXO, Oven Controlled XO:

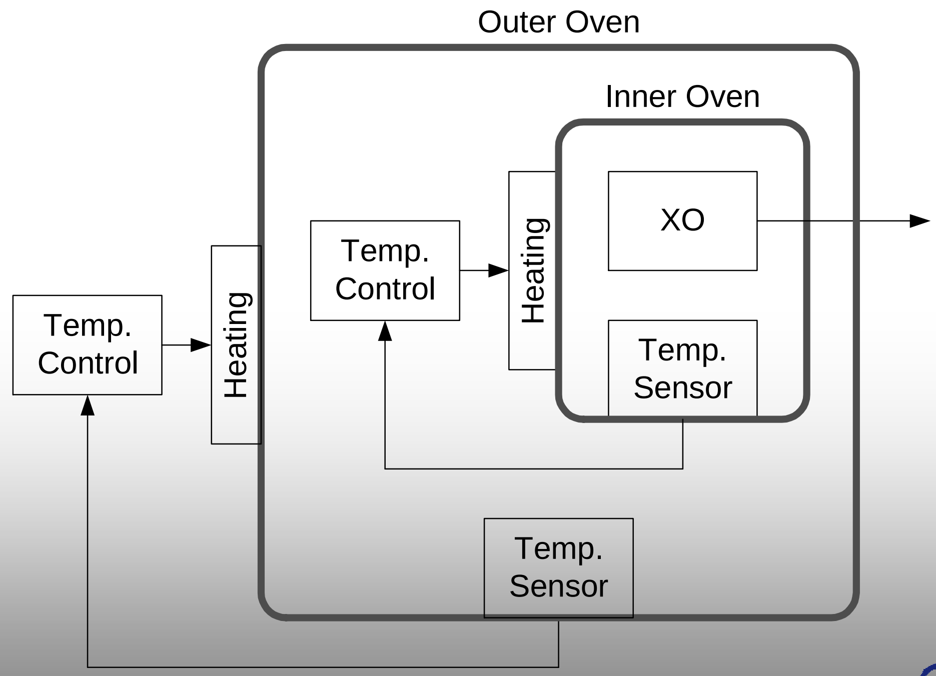
- A control loop maintains the oven containing the XO at (nearly) constant temperature.
- 5E-9 to 5E-8 over [-30°C to 60°C]



XO Categories rel. Temp. Control

DOCXO, Double Oven Controlled XO:

- Two temperature controlled ovens, one inside the other.
- 1E-10 to 5E-9 over [-30°C to 60°C]



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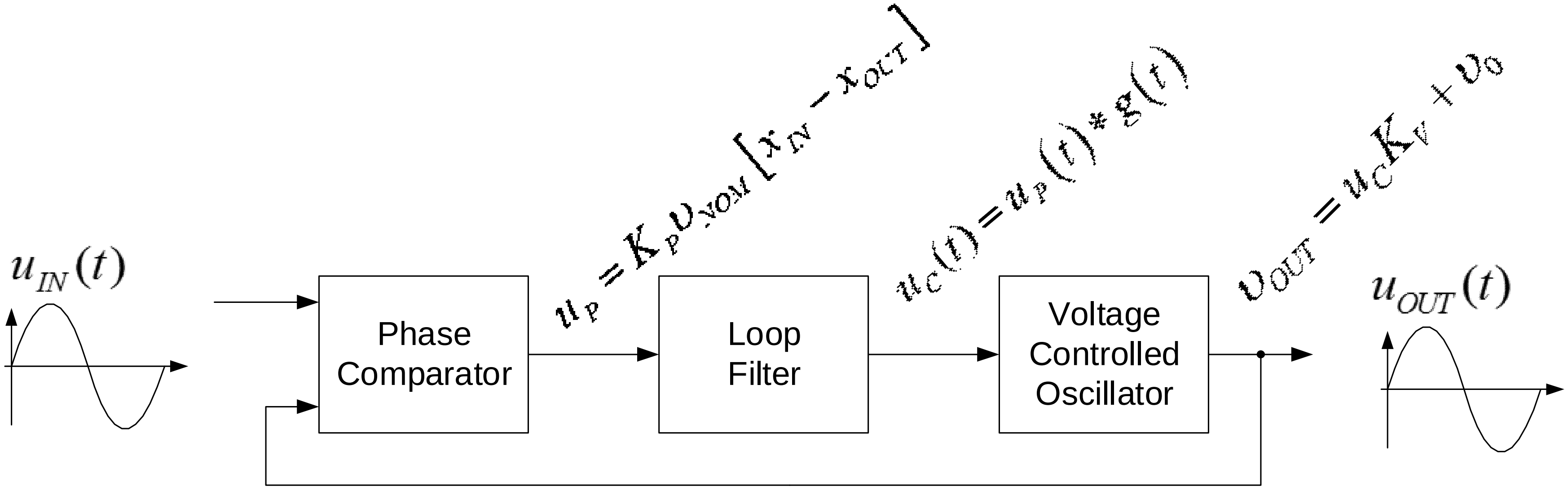
Summary

Oscillator type	Temperature sensitivity (fractional frequency vs temperature)
XO	1E-7 / °C
TCXO	5E-8 to 5E-7 [-55°C to 85°C]
SOCXO	5E-9 to 5E-8 [-30°C to 60°C]
DOCXO	1E-10 to 5E-9 [-30°C to 60°C

2. Phase-Locked Loops (PLL)

PLL: Working principle



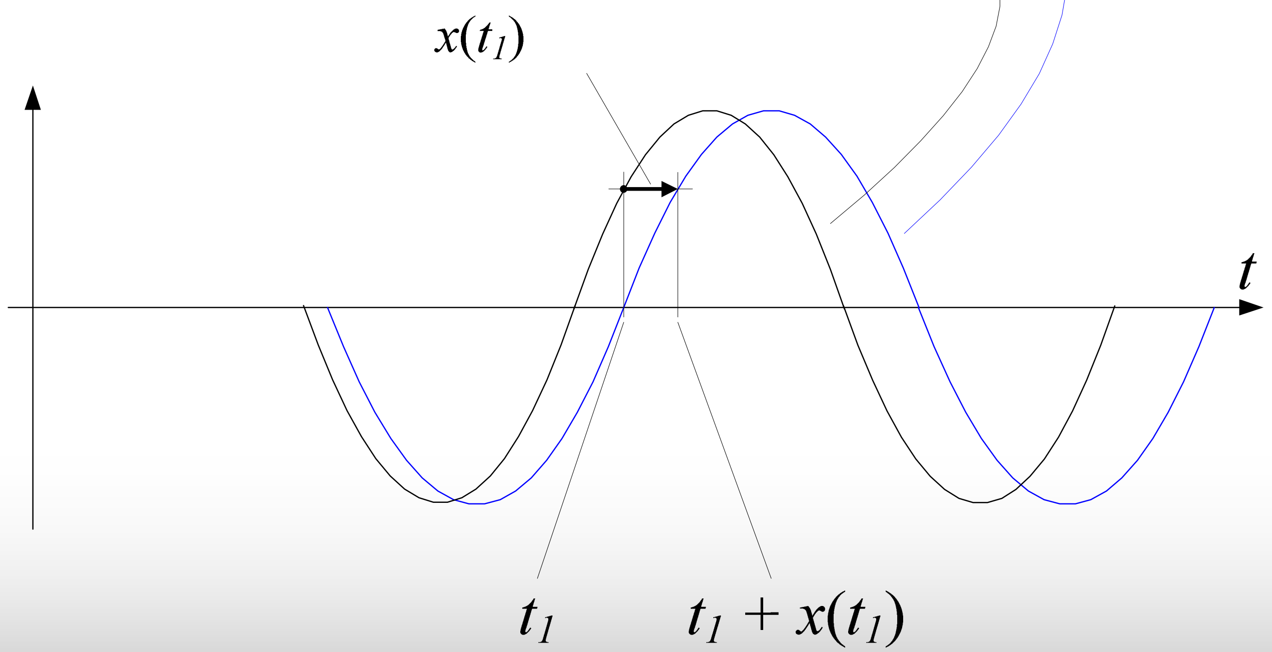
$$u_{IN}(t) = A \cdot \sin\left\{2\pi\upsilon_{NOM}\left[t + x_{IN}(t)\right]\right\} = A \cdot \sin\left\{2\pi\upsilon_{IN}(t) + \varphi_{0,IN}\right\}$$

$$u_{OUT}(t) = A \cdot \sin\left\{2\pi\upsilon_{NOM}\left[t + x_{OUT}(t)\right]\right\} = A \cdot \sin\left\{2\pi\upsilon_{OUT}(t) + \varphi_{0.OUT}\right\}$$

Phase-time deviation $x(t)$

$$\text{nominal signal} = \sin\{2\pi\upsilon_{NOM} t\}$$

$$\text{actual signal} = \sin\{2\pi\upsilon_{NOM}[t + x(t)]\}$$



Note: Phase-time x = random component only
Time Error TE = random and deterministic components

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Transfert function «Input-to-Output»

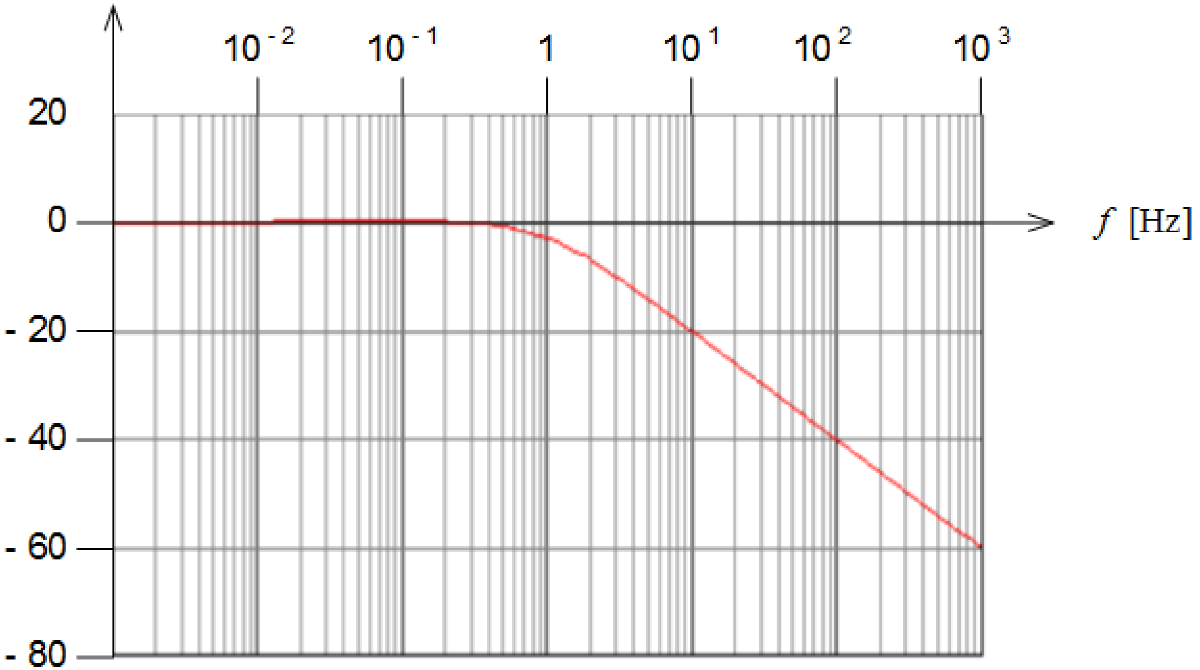
$$x_{OUT}(t) = x_{IN}(t) * h_{IN}(t)$$

$$X_{OUT}(s) = X_{IN}(s) \cdot H_{IN}(s)$$

where $h_{IN}(t) =$ impulse response

$H_{IN}(s) =$ transfer function $= \text{Laplace}\{h_{IN}(t)\}$

$20\log\left|H_{IN}(j2\pi f)\right|$ [dB]



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Transfer function «Oscillator-to-Output»

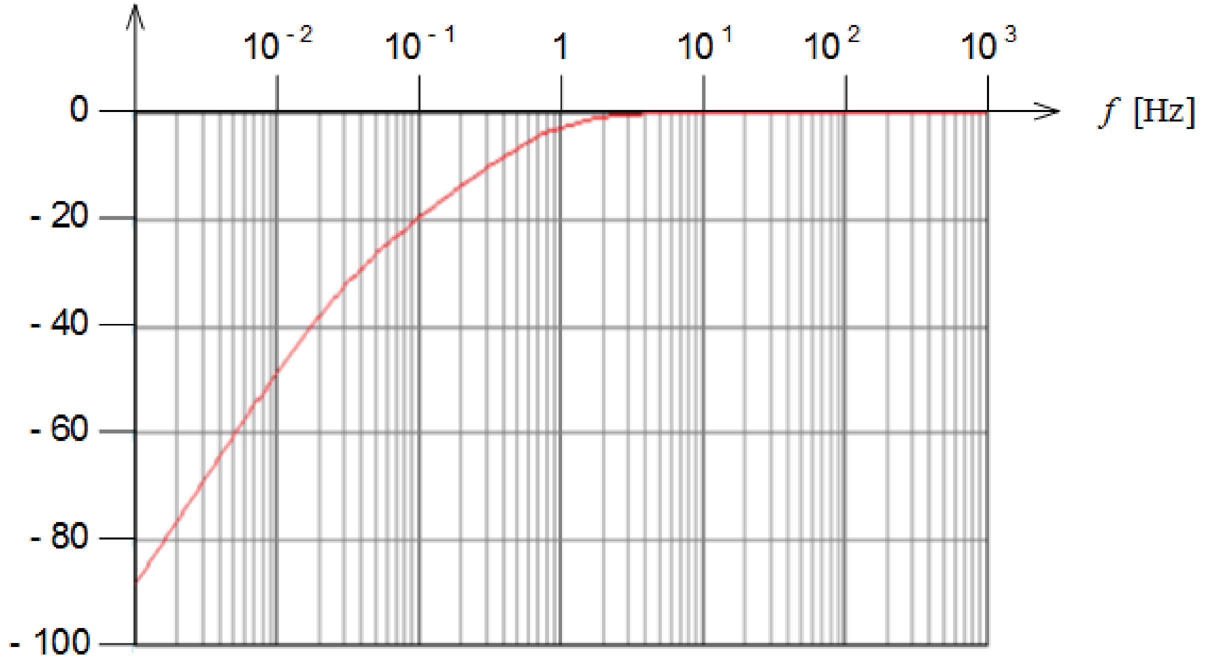
$$x_{OUT}(t) = x_{OSC}(t) * h_{OSC}(t)$$

$$X_{OUT}(s) = X_{OSC}(s) \cdot H_{OSC}(s)$$

where $h_{OSC}(t) =$ impulse response

$H_{OSC}(s) =$ transfer function $= \text{Laplace}\{h_{OSC}(t)\}$

$20\log|H_{OSC}(j2\pi f)|$ [dB]



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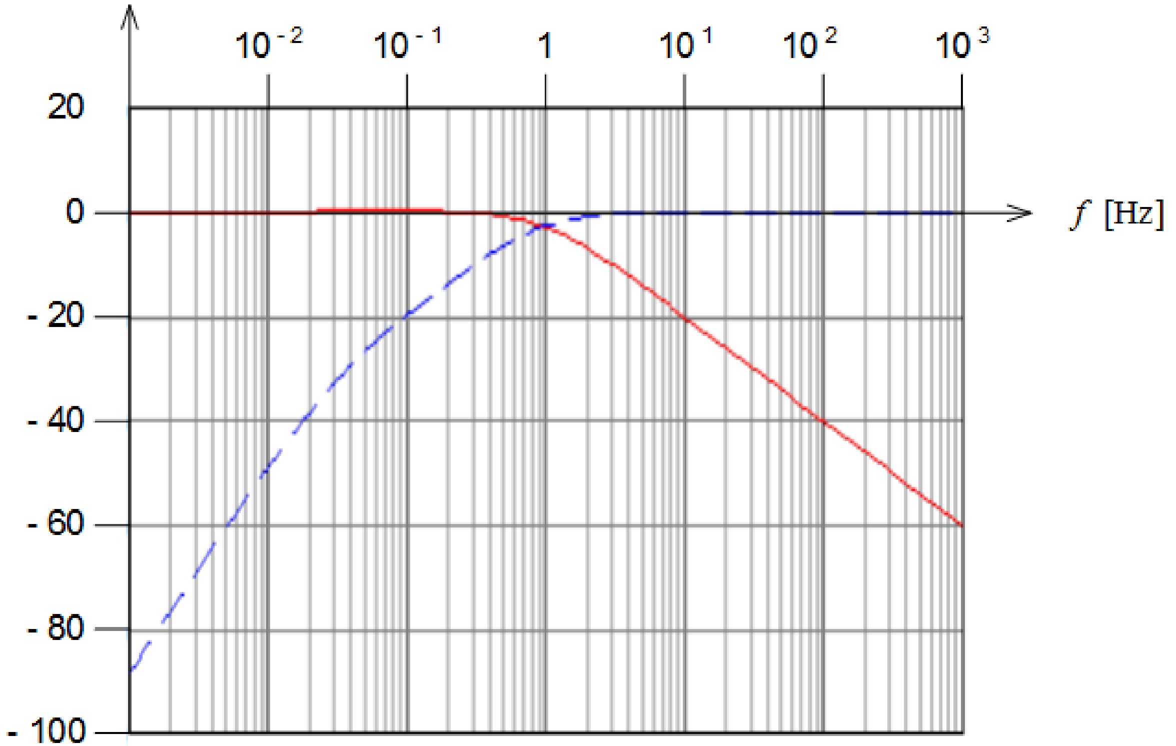
Both transfer functions

$20\log\left|H_{IN}\left(j2\pi f\right)\right|$ [dB]

$20\log\left|H_{OSC}\left(j2\pi f\right)\right|$ [dB]



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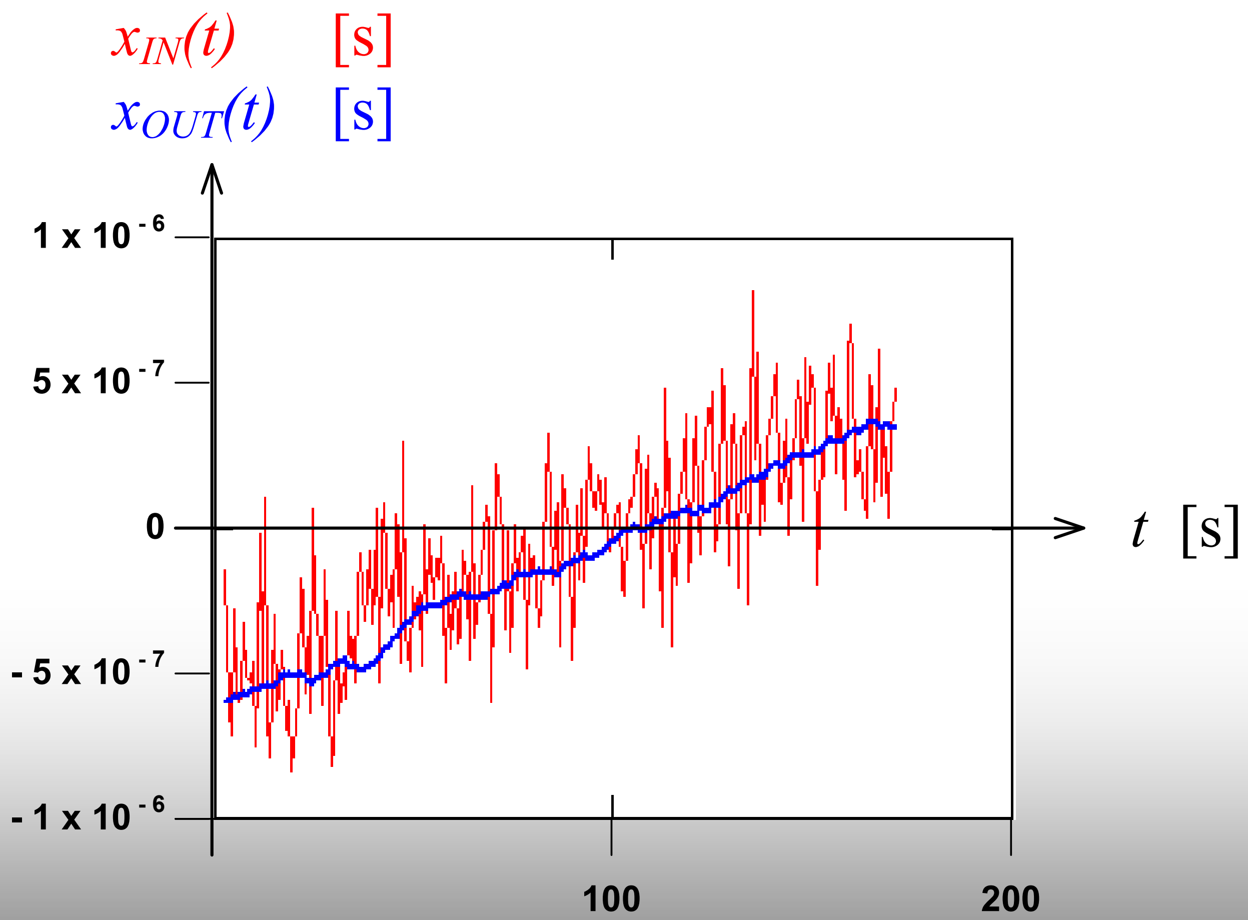
PLL: Jitter filtering



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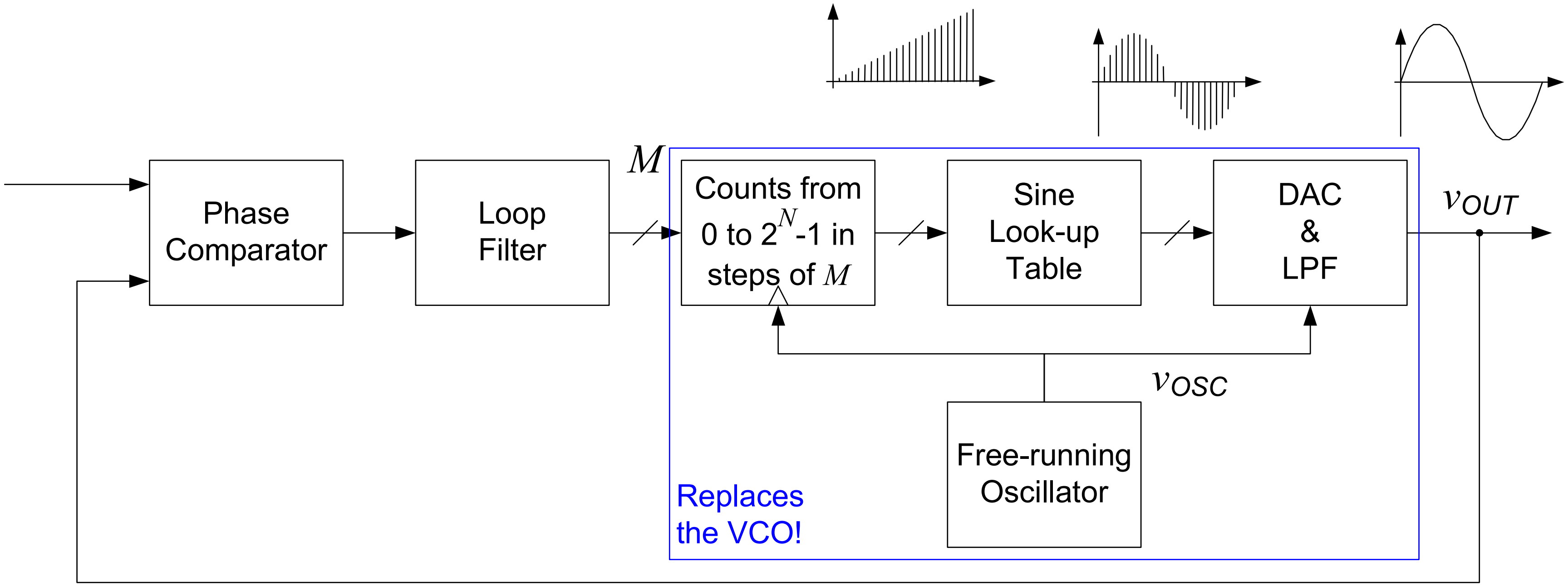
PLL terminology

- Hold-in range: largest offset between a PLL's input frequency and a specified nominal frequency, within which the PLL maintains lock as the frequency varies arbitrarily slowly over the frequency range
- Pull-in range: largest offset between a PLL's input frequency and a specified nominal frequency, within which the PLL will achieve locked mode
- Pull-out range: The offset between a PLL's input frequency and a specified nominal frequency, within which the PLL stays in the locked mode and outside of which the PLL cannot maintain locked mode, irrespective of the rate of the frequency change.
- Pulling range: term which applies to Voltage Controlled Oscillators (VCO), not to PLLs; maximum change in output frequency that can be attained via the control voltage

PLL with Direct Digital Synthesis



DAC = Digital-to-Analog Converter

LPF = Low-pass Filter

$$\upsilon_{OUT} = \frac{M}{2^N}\upsilon_{OSC}$$

where $M =$ output of the digital loop filter (integer)

$N =$ size of the counter in bits (integer)

$\upsilon_{OUT} =$ frequency of output signal $u_{OUT}(t)$

$\upsilon_{OSC} =$ free-run frequency of the oscillator

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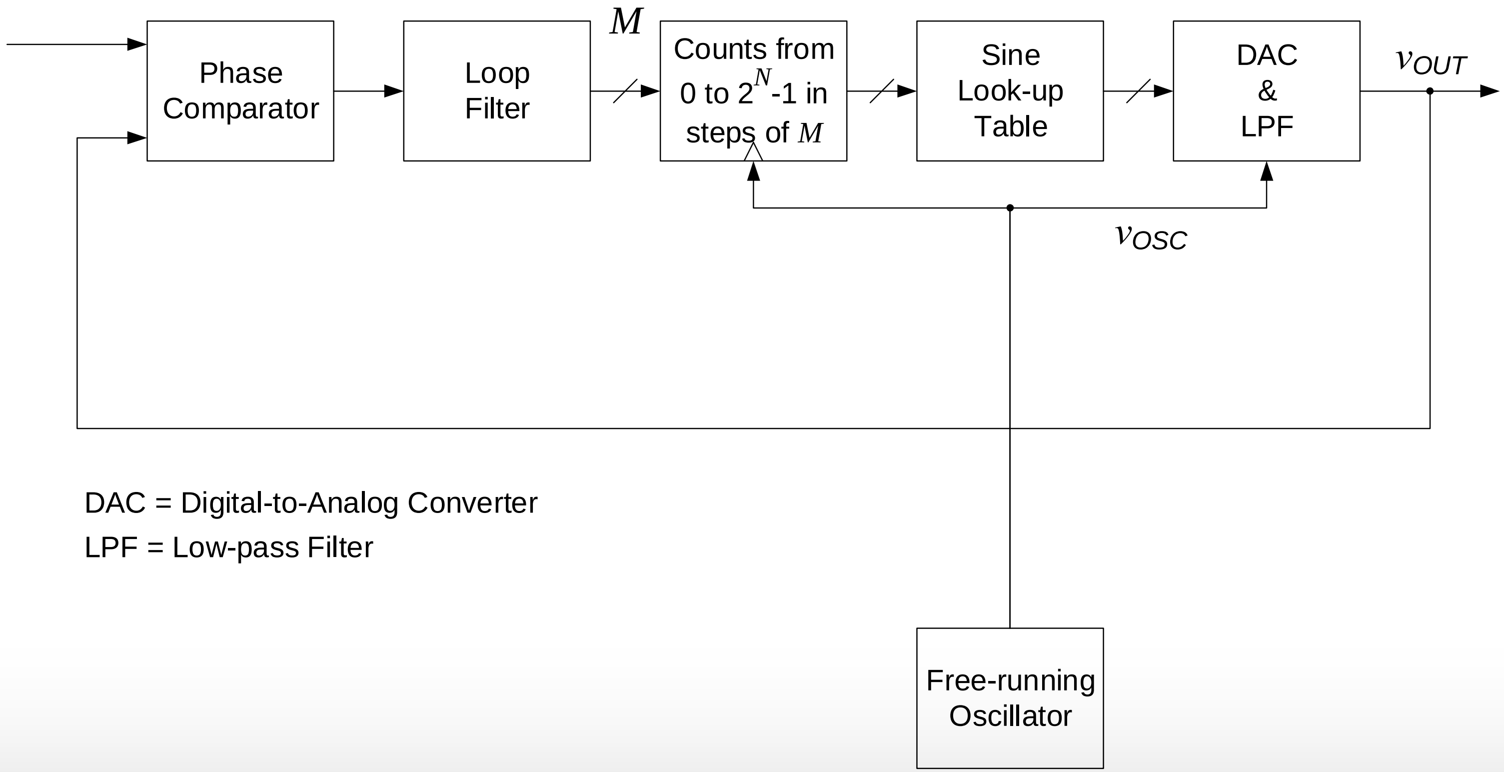
PLL with VCO and with DDS compared

	Pros	Cons
PLL with VCO	•Very low phase noise	•PLL's pull-in range depends on VCO's pulling range •Requires VCO
PLL with DDS	•Configurable pull-in range •Requires only free-running oscillator	•Some quantization phase noise

Imagine the following:



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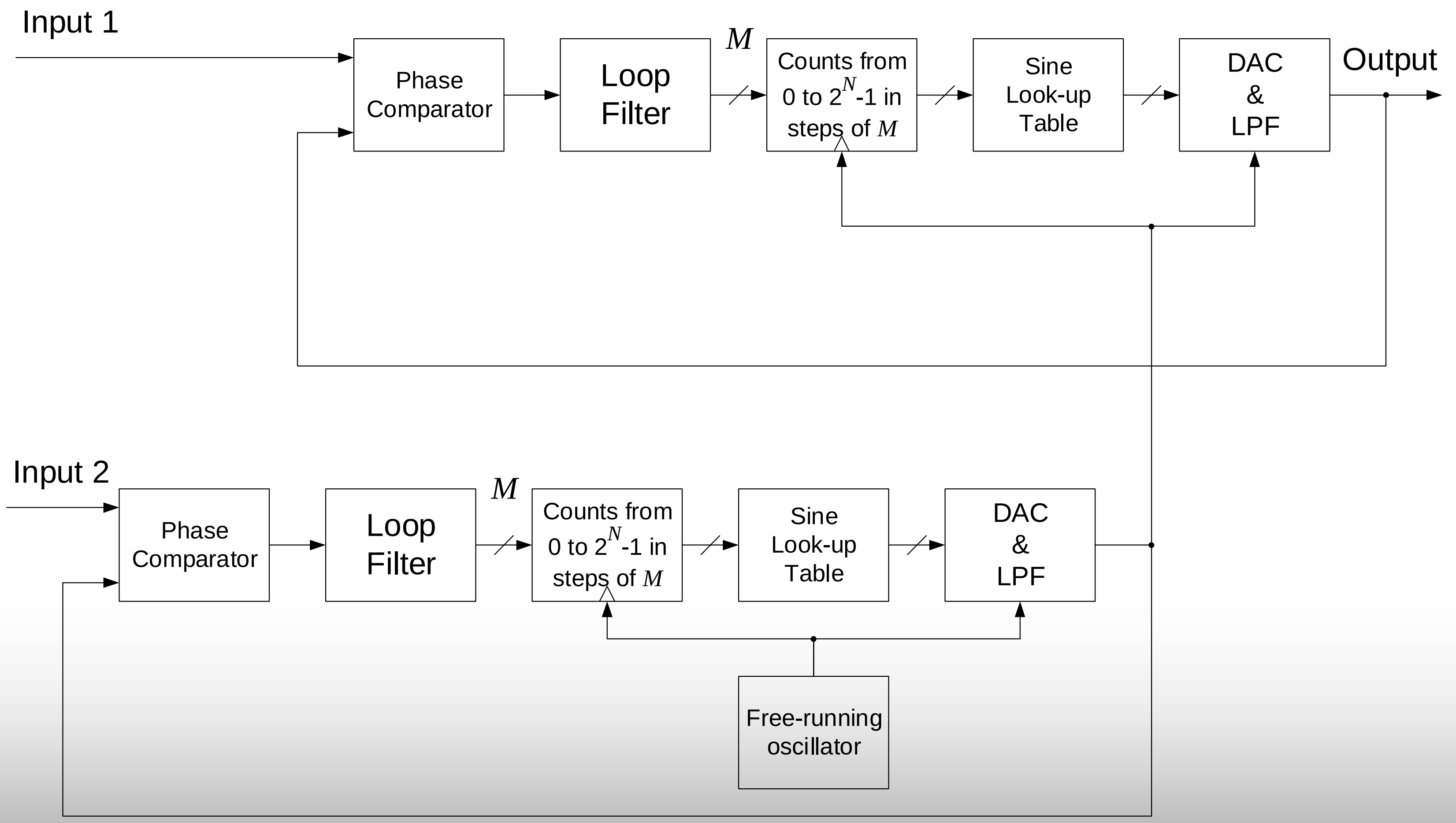

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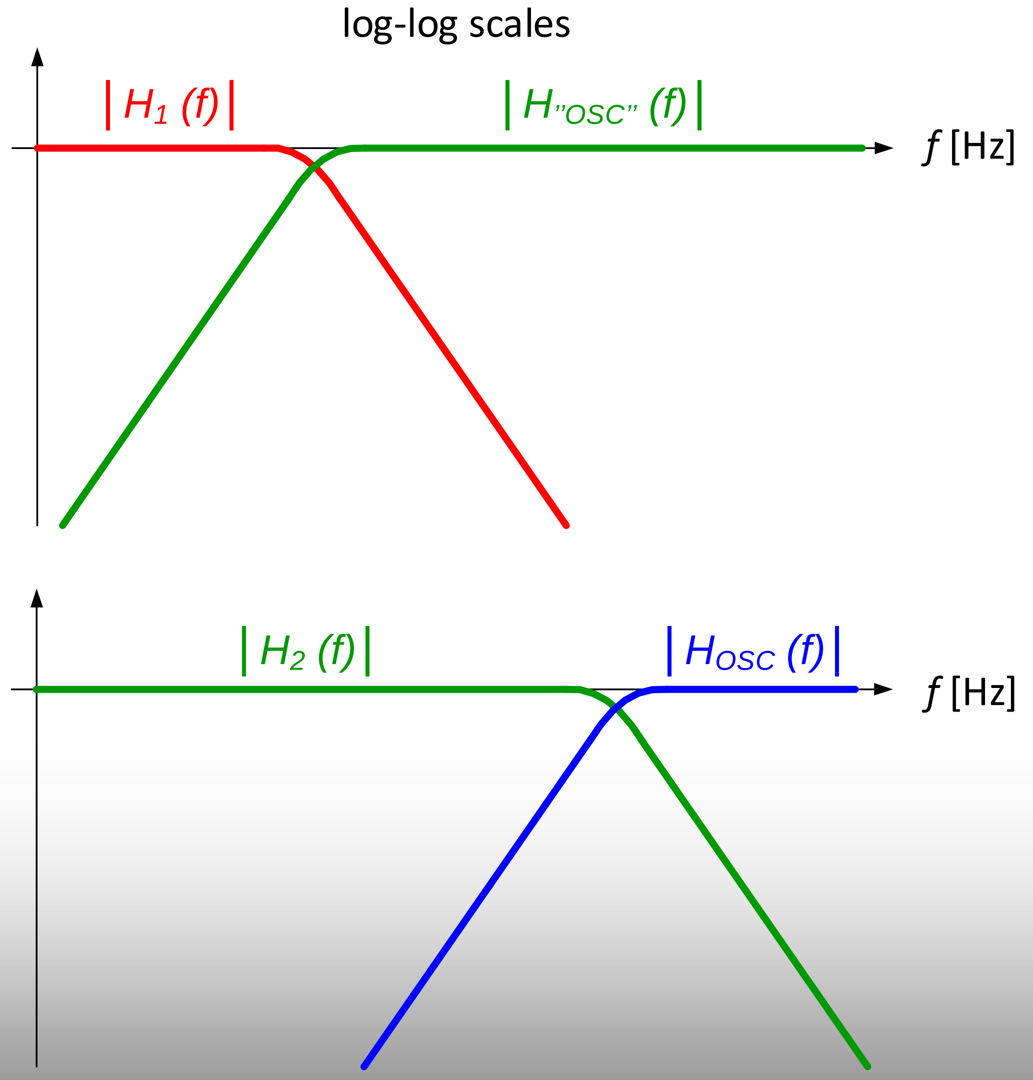
Imagine the following:



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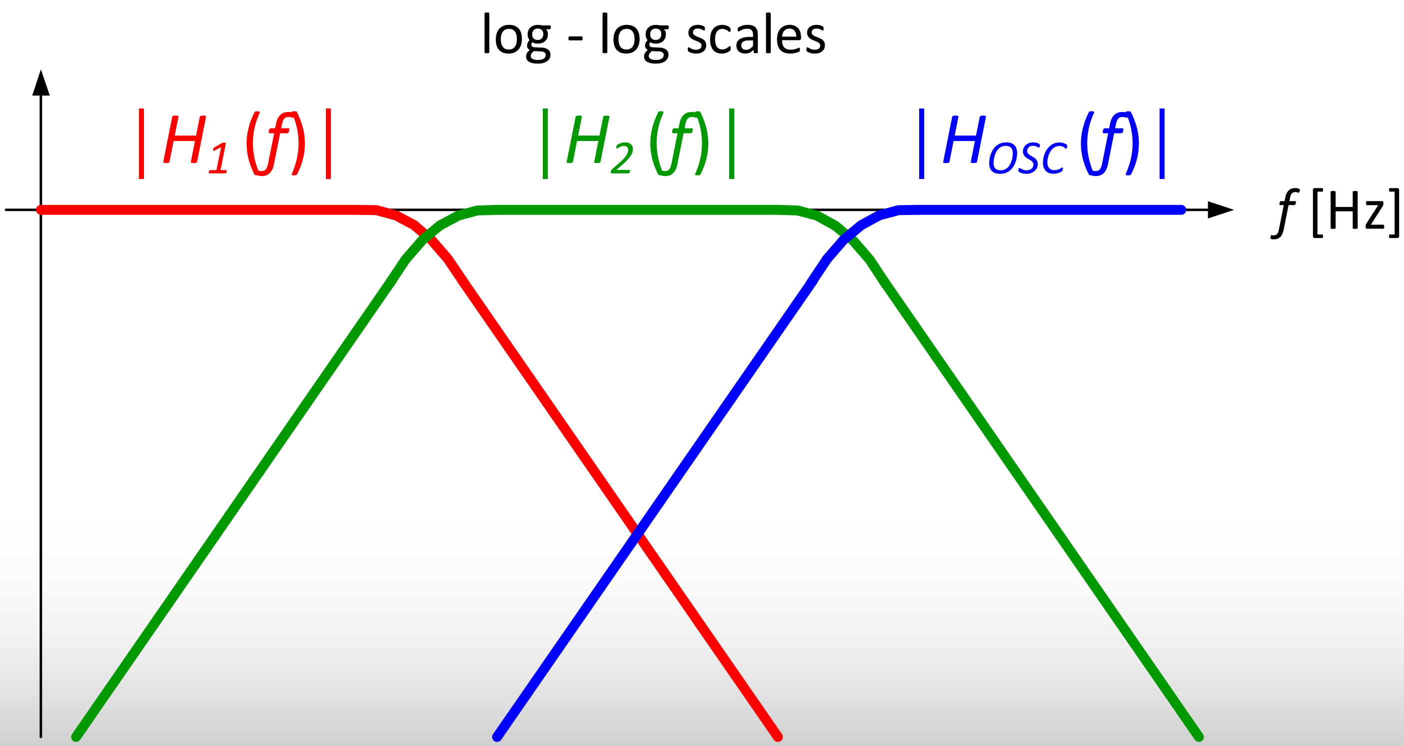
What do the transfer functions look like?



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See you all at the Welcome Reception at 5:00 PM (sponsored by Oscilloquartz)

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