Measuring of small AC signals using lock-in amplifiers.

- Narrow band selective amplifiers + amplitude detector.
- Lock-in amplifiers
Lock-in amplifier technique

Simplified block diagram of a lock-in amplifier

Signal in \rightarrow \text{Signal amplifier} \rightarrow \text{PSD*} \rightarrow \text{Low-pass filter} \rightarrow \text{DC amplifier} \rightarrow \text{output}

Reference in \rightarrow \text{VCO**} \rightarrow \text{PSD*} \rightarrow \text{Reference out}

*PSD - phase sensitive detector;  
**VCO - voltage controlled oscillator

Lock-in amplifier. How it works.
Lock-in amplifier technique

Phase shift

$\varphi = \pi/4$, $V_{out} = 0.72 V_{in}$

$V_{in} = \sin(\omega t + \pi/4)$

$V_0 \sin(\omega t + \varphi)$

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The dependence of pattern of the output signal after demodulator on phase shift between input and reference signals.

\[ V_0 \sin(\omega t + \varphi) \]

- \( \varphi = 0, \ E_x = E_{in} \)
- \( \varphi = \pi/4, \ E_x = 0.72E_{in} \)
- \( \varphi = \pi, \ E_x = -E_{in} \)
- \( \varphi = \pi/2, \ E_x = 0 \)
- \( \varphi = 3\pi/2, \ E_x = 0 \)
Lock-in amplifier technique. Simple math.

\[ U_x = U_{x0} \sin(\omega_1 t + \theta_1) \]  - input signal

\[ U_r = \sin(\omega_2 t + \theta_2) \]  - reference signal

\[ U_{\text{de mod}} = U_x \cdot U_r = U_{x0} \sin(\omega_1 t + \theta_1) \cdot \sin(\omega_2 t + \theta_2) = \]

\[ \frac{U_{x0}}{2} \left[ \cos(\omega_1 + \omega_2) t + \theta_1 + \theta_2 \right] + \cos(\omega_1 - \omega_2) t + \theta_1 - \theta_2 \right] \]

\[ \omega_1 \neq \omega_2 \]

\[ \omega_1 = \omega_2 = \omega \]

\[ U_{\text{de mod}} = \frac{U_{x0}}{2} \left[ \cos(2\omega t + \theta_1 + \theta_2) + \cos(\theta_1 - \theta_2) \right] \]

and after low-pass filtering

\[ U_{\text{de mod}} = \frac{U_{x0}}{2} \cos(\theta_1 - \theta_2) \]
In many technical applications we need to measure both components ($E_x$, $E_y$) of the input signal. To do this most of the modern lock-in amplifiers are equipped by two demodulators.

$$E_{in} = E_0 \sin(\omega t + \varphi)$$

- $E_0$ is the input signal amplitude.
- $\omega$ is the angular frequency.
- $t$ is time.
- $\varphi$ is the phase shift.

The demodulation process separates the signal into $E_x$ and $E_y$ components.

**Diagram:**
- The input signal $E_{in}$ is modulated by a sinusoidal function.
- The signal is demodulated into $E_x$ and $E_y$ components.
- The phase difference $\varphi$ affects the orientation of the $E_x$ and $E_y$ components.

$E_x$ and $E_y$ are the resulting components after demodulation.
In 1961, Princeton Applied Research was founded by a group of scientists from Princeton University and the Plasma Physics Laboratory. With a desire to establish significant improvements to research instrumentation the team developed the first commercial lock-in amplifier in 1962.

**Model HR-8**

\[ f \text{ range: } = 5\text{Hz} \div 150\text{kHz} \]
Lock-in amplifier technique

Analog and digital lock-ins

SR510 & SR530
Lock-In Amplifiers

- 0.5 Hz to 100 kHz frequency range
- Current and voltage inputs
- Up to 80 dB dynamic reserve
- Tracking band-pass and line filters
- Internal reference oscillator
- Four ADC inputs, two DAC outputs
- GPIB and RS-232 interfaces

Analog lock-ins from Stanford Research Systems
Block-diagram of analog lock-in

SR530
Lock-in amplifier technique

Analog lock-ins

SR124

Low noise, all analog design
No digital interference
0.2 Hz to 200 kHz measurement range
Low noise current and voltage inputs
Harmonic detection (f, 2f, or 3f)
Selectable input filtering
Lock-in amplifier technique

Digital lock-ins

Two DSP lock-in amplifiers: SR830 from Stanford Research Systems and 7265 from Signal Recovery.

The main advantages of digital lock-ins:
* high phase stability;
* broad frequency range;
* ideal for low and ultra low frequencies (up to 0.001Hz)
* harmonics up to 65,536 (7265), 19,999 (SR830).
Lock-in amplifier technique

Analog and digital lock-ins

Block-diagram of digital lock-in
Lock-in amplifier technique

Block-diagram of digital lock-in

SR830 digital lock-ins

GPIB

V_{in}

Input amplifier + filters

Main ADC

DSP

Output filters

Function generator

clock

ADC1

ADC2

ADC3

ADC4

Ref. out

ADC1

DAC1

DAC1

DAC1

DAC1

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(i) Applying a small test signal (locked to the reference signal) to the studied object

Examples: frequency domain spectroscopy (second sound), tunneling spectroscopy (analysis of the I-V curves), dielectric spectroscopy etc.
Modulating of the studied signal by the signal locked to the reference signal

Examples: fluorescence experiment
Lock-in amplifier technique: some applications

Experimental setup for measurement of the dielectric susceptibility (electrical conductivity) in the temperature range 15-450K
Scanning of the frequency of the AC signal applied to transmitter we can find the frequencies of the acoustical resonance.

Lock-in amplifier technique: some applications

Second sound experiment

Transmitter (heater)

Receiver

He4

AC drive signal

T~1.96K

R (V)

f (Hz)
Lock-in amplifier technique: some applications

Optical pumping

\[ \Delta H \approx 0.01 \text{G} \]
Lock-in amplifier technique: some applications

- Function generator
- DMM
- SR830 lock-in

Sweep coil

Rb cell

Optical pumping

$B_0$ - main field

$B_0 + B_1 \sin(\omega t)$

From TeachSpin detector

reference
Optical pumping

The choice of amplitude modulation

\[ I_{\text{sweep}} = \frac{V_{FG}}{5.1k\Omega} \]

\[ B_1 = k_{\text{sweep}} \cdot I_{\text{sweep}} \]

\[ K_{\text{sweep}} \approx 0.6G/A \]

If \( V_{FG} = 1V \)

\( B_1 \approx 0.12mG \)
Lock-in amplifier technique: some applications

Optical pumping

Analog detector record ($I(f)$)

Lock-in detector record $\frac{\partial I}{\partial H}(f)$

Mapping 0.5-2.5A from March 1st 2012: Graph6
Lock-in amplifier technique: some applications

\[ eV_{\text{DC}} + eV_{\text{AC}} \]

Tunneling spectroscopy

\[ E \]

Empty states

Occupied States

\[ E_F \]
Lock-in amplifier technique: some applications

Tunneling spectroscopy

\[ eV_{DC} \] only

Sample # (n3-n9) Al-Al₂O₃-Pb

T = 1.5475 ± 7e - 4K

Courtesy of Anna Miller and Everett Vacek

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Lock-in amplifier technique: some applications

Tunneling spectroscopy

$eV_{DC} + eV_{AC}$

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Lock-in amplifier technique: demo

- Function generator
- Noise
- Lock-in amplifier

demo lock-in