Introduction

This Technical Note discusses the reasons why users choose lock-in amplifiers for their measurements and defines the terms used to describe the instruments' performance. It is assumed that readers already have a basic understanding of the operation of the lock-in amplifier, but if this is not the case then the PerkinElmer Instruments (Signal Recovery) Technical Note TN1000, "What is a Lock-in Amplifier?", may prove helpful.

Why use a Lock-In Amplifier?

The main reason for using a lock-in amplifier is to recover signals from noise. Consider the following example.

Let the signal to be measured be a:-

   ◆   20 nV sinewave at 50 kHz.

Obviously some amplification is needed before it can be measured, whether on an AC voltmeter, an oscilloscope or a lock-in amplifier. Any amplifier will add noise to the signal, but for a good unit this might be:-

   ◆   Input noise ≤ 4 nV$\sqrt{\text{Hz}}$

at a:-

   ◆   Bandwidth of 1 MHz, and a
   ◆   Gain of 1000.

For the above signal the output signal of this amplifier will be:-

   ◆   20 µV (1000 × 20 nV)

accompanied by:-

   ◆   4 mV r.m.s. ($\sqrt{1 \text{ MHz}} \times 4$ nV × 1000)

of broadband noise. Clearly it is impossible to measure the signal of interest in the presence of this level of noise, unless something is done to isolate it. One means of achieving this is the use of a filter before the amplifier.

If the signal is first passed through a bandpass filter with:-

   ◆   a center frequency of 50 kHz, and
   ◆   a Q of 100 (this implies a 3 dB bandwidth of 500 Hz - a specification which is difficult to attain),

then any signal within this 500 Hz bandwidth will be detected. The noise within this bandwidth is:-

   ◆   89 µV ($\sqrt{500 \text{ Hz}} \times 4$ nV × 1000)

but the signal is still only:-

   ◆   20 µV

and so it will still not be possible to make a measurement.

Now consider feeding the same signal to a lock-in amplifier. This can detect a frequency of 50 kHz with a noise bandwidth of 0.125 Hz, when the output time constant is 1 second and the filter slope is 12 dB/octave.

The noise accompanying the signal now will be only:-

   ◆   1.4 µV ($\sqrt{(0.125 \text{ Hz}} \times 4$ nV × 1000))

implying that it will be possible to make a measurement of the 20 µV input signal. Performance can be further improved by using longer time constants, at the expense of increased time to complete the measurement. As specified, it would take around 5 seconds for the lock-in amplifier's output to stabilize following the application of the 20 µV signal. Hence the signal has *been recovered from the noise* by the lock-in amplifier.

What does a Lock-In Amplifier Measure?

Using Fourier's theorem, any input signal, including the noise accompanying it, can be represented as the sum of many sinewaves of different amplitudes, phases and frequencies. The phase-sensitive detector in the lock-in amplifier multiplies all these components by a signal at the reference frequency. In the case of a **sinewave-responding** (also known as a **fundamental responding**) instrument, the output is a DC signal proportional to the component of the input signal which is exactly in phase and frequency lock with the reference signal. **Squarewave-responding**, or **flat-responding**, lock-in amplifiers give a DC output proportional to the components of the input signal in phase lock with the reference signal and its odd harmonics, where the relative response at the "n"th harmonic is given by $1/n$.

The two different types of response are important when comparing the measurements made using a lock-in amplifier with those made using other instruments, for example an oscilloscope. Consider the case of a 2 volt peak-to-peak noise-free sinusoidal signal, which can be expressed mathematically as:-

$$V = \sin \omega t$$

where $\omega = 2 \pi$

Both the sinewave-responding and the squarewave-responding lock-in amplifiers, when locked to the reference frequency f and correctly phase-adjusted for maximum response, would indicate a reading of:-

$$V = \sqrt{2}/2 \text{ volts}$$
$$= 0.707 \text{ volts}$$

This is the r.m.s. value of a 2 volt peak-to-peak sinewave.

Now consider the case of a 2 volt peak-to-peak squarewave at frequency f, which according to Fourier's theorem can be expressed as:-

$$V = 4/\pi \sin \omega t + 4/3\pi \sin 3\omega t + 4/5\pi \sin 5\omega t \text{ ...}$$

If this signal were applied to a sinewave-responding lock-in amplifier, the instrument would extract the first (fundamental) component and the display would read:-

$$V = 4/\pi \sqrt{2}/2$$
$$= 0.9 \text{ volts}$$

If the same signal were applied to a squarewave-responding lock-in amplifier, each of the harmonics would contribute to the output signal, and the display on the lock-in amplifier would read:-

$$V = 4/\pi \sqrt{2}/2 \, ((1/1)^2 + (1/3)^2 + (1/5)^2 \text{ ...})$$
$$V = \sqrt{2}/2 \, 4/\pi \, (1.23)$$
$$V = 1.11 \text{ volts}$$

In other words, if the input signal is a squarewave, such as is the case in most chopped light signals, a squarewave-responding lock-in amplifier will detect about 23 % (i.e. 1.11/0.9) more signal than is the case when a sinewave-responding lock-in amplifier is used.

Peak-to-Peak or R.M.S.?

When measuring *sinusoidal* input signals, lock-in amplifiers generally display the measured value in volts r.m.s., so that if for example the lock-in amplifier shows a reading of 100 mV, the component of the input signal at the reference frequency is 100 mV r.m.s., or 283 mV peak-to-peak.

Phase Measurements

Lock-in amplifiers always use degrees as the unit of phase, although in some of the mathematics used to describe their operation radians are used. Similarly, frequency f is always measured in hertz, although the equations are often simpler if angular frequency, usually termed "ω", is used, where:-

$$\omega = 2\pi f$$

Lock-In Amplifier Specifications

The final section of this technical note seeks to explain some of the specification terminology that may be encountered when choosing a lock-in amplifier.

Input Amplifier

This may be either a voltage or a current input device. Voltage inputs offer the highest possible impedance to the signal to be measured so that they do not affect its level. Good lock-in amplifiers will present an input impedance of at least 10 MΩ.
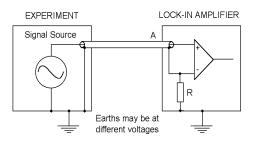

Figure 1, Single-ended Voltage Input

The **single-ended input** (figure 1) is the most commonly used configuration, in which the lock-in amplifier amplifies the difference between the signal at the inner and outer conductors of the input connector. The outer connector, or shield, is not forced to ground potential but is instead connected via a resistor of typically 100 to 1000 ohms. This avoids possible "ground loops" between the source and the instrument, due to differing ground potentials, by allowing the shield to "float" so that the lock-in amplifier can sense the signal source ground.
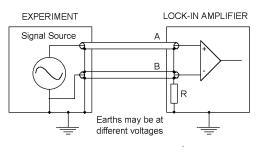

Figure 2, Differential Voltage Input

A **differential input** (figure 2) has two connectors and amplifies the difference in voltage between them. If the two cables used to connect them to the signal source are identical, then any spurious noise pick-up will affect both cables equally and be rejected by the common mode rejection capability of the differential input amplifier. The quality of this rejection is specified by the **Common Mode Rejection Ratio** or **C.M.R.R.**; a figure of at least 100 dB at 1 kHz should be expected, corresponding to the ability to measure a 10 µV signal in the presence of 1 volt of common mode interference.

A **current input** is designed to absorb all of the current offered to it, and as such should have as low an input impedance as possible. It should be used when the signal source impedance is high. Usually in lock-in amplifiers the current input is specified

by a **conversion gain**, typically of 10^8 or 10^6 V/A. Hence to find the overall sensitivity of the lock-in amplifier in amps the current conversion range chosen must be multiplied by the full-scale voltage sensitivity being used. The **gain accuracy** of the amplifiers used in the signal channel is a measure of the initial accuracy of the gain calibration, so that for example if a 100 mV signal is being measured, a gain accuracy of 1 % implies that the lock-in amplifier will display a reading between 99 mV and 101 mV.

The **gain stability** may also be specified and defines how the initial gain may be affected by changes in both time and temperature. In a normal laboratory environment it is usual to consider the effects of a 10 °C change in temperature as being the largest that is likely to be encountered.

Dynamic reserve is a term which is often used to describe the signal recovery performance of lock-in amplifiers. It is a measure of how large a discrete asynchronous interfering signal can be before the lock-in amplifier starts to measure the required signal incorrectly. Typically this is determined as the point where the output is in error by 5 %, which is a more demanding specification than simply saying that it is the point where the lock-in amplifier is overloaded. It is usually expressed in decibels (dB), where

The same dynamic reserve is not, of course, available on all sensitivity settings, since the peak input is restricted to the range of linear operation of the input amplifier, which is typically a few volts. For example, 60 dB of dynamic reserve is not available at a 1 V full-scale sensitivity since this would imply a 1 kV input capability.

Commercially available lock-in amplifiers offer dynamic reserves up to 130 dB, implying the ability to measure, for example, a 100 nV signal in the presence of a 300 mV interfering signal.

Often confused with dynamic reserve, **dynamic range** is the ratio of the peak signal input that can be measured without overloading to the minimum detectable signal.

Reference Channel

The reference input has to accept the applied reference signal and generate from it an accurate reference frequency for the lock-in amplifier to use. Reference circuits should be capable of responding to any periodic waveform, with two zero crossings per cycle, by adjusting the trigger threshold. The minimum and maximum reference levels are usually specified as well. Any lock-in amplifier, when operating from an external reference, needs time to establish lock following a change in the applied reference. This is defined as the **lock acquisition time**.

The **phase-shifter resolution** defines the smallest phase increment with which the reference drive to the phase-sensitive detectors can be adjusted, and the **phase drift** specification shows how a specified phase will change with temperature and, possibly, time.

Some experiments call for the simultaneous measurement of signals that are in *quadrature* (i.e. shifted by 90° relative to one another), which requires the use of a dual phase lock-in

amplifier. When the quadrature signal is very much smaller than the in-phase signal, **phase noise**, which is the random variation in the phase difference between the signal and reference inputs to the phase-sensitive detector, can become a problem.

As an example, consider that it is necessary to resolve:-

- ◆ an in-phase signal of 1 mV

and

- ◆ a quadrature signal of 1 µV

The phase noise of a good lock-in amplifier might be:-

- ◆ 10m° r.m.s.

at a

- ◆ time constant of 100 ms.

In this case the "breakthrough" from the in-phase to the quadrature component is:-

$$V = \sin(0.010°) \times 1 \text{ mV}$$
$$= 174 \text{ nV}$$

Hence the quadrature signal of 1 µV could easily be measured.

Orthogonality is a specification which applies only to dual phase lock-in amplifiers and refers to the accuracy of the nominal 90° phase shift between the reference drives to the two phase-sensitive detectors.

Output Channel(s)

In a single phase lock-in amplifier, there will be only one output channel, but in a dual phase unit there are two.

The output from the phase-sensitive detector passes to a low-pass filter. Usually filters are specified by the frequency at which their transmission is 3dB down on the passband, but since the value of this for a lock-in amplifier's output filter is very low, they are usually specified instead by a **time constant** which is inversely proportional to the -3 dB frequency.

Although the time constant defines the frequencies below which the filter will pass signals, the shape of the **roll-off** with increasing frequency is also important. Usually the filters used in lock-in amplifiers exhibit the same response as a resistor-capacitor (RC) filter, which shows a 6 dB/octave roll-off. This implies that for frequencies well above the passband, if the frequency doubles (an octave) the response falls by 6 dB, or halves.

Filter stages are often "stacked" to provide 12 dB, 18 dB and even 24 dB/octave roll-off. Generally the larger the roll-off, the shorter the time constant needed to achieve a given stability of output. In some cases, however, such as when the lock-in amplifier is part of a feedback control loop, a roll-off greater than 6 dB/octave should not be used since this can cause instabilities due to positive feedback.

In any lock-in amplifier with an analog output stage, the DC amplifier that is used exhibits drift with temperature. Usually it is possible to trade off this **DC stability** with dynamic reserve, but

in any good lock-in amplifier even with the poorest setting of say 500 ppm/ºC, a 10 ºC temperature drift results in an error of less than 0.5 % of full-scale. These settings need only be used when there is a lot of interfering noise, in which case the errors are usually small when compared with the effects of the noise.

In some experiments coherent pick-up is a problem and the lock-in amplifier will indicate an output even if there is nominally no signal reaching the detector. This error may be removed by **offset** controls, which add to, or subtract from, the outputs a predetermined amount so as to bring them to zero.

Modern lock-in amplifiers invariably incorporate a microprocessor which allows them to offer the user automatic functions. **Auto-phase, auto-sensitivity, auto-measure** (which combines auto-sensitivity and auto-phase into a single operation) and **auto-offset** are examples which are commonly included. The microprocessor also facilitates instrument operation from a computer, typically via a GPIB (IEEE-488) and/or RS232 connection.

Many units provide an **internal oscillator** which can be used as a source of excitation and reference to the experiment. The oscillator usually provides a sinewave output with user-adjustable voltage and frequency.

Most lock-in amplifiers also include the capability of detecting signals at twice the reference frequency, which is called the **2F mode**. This is very useful in experiments using non-linear devices. Some units also provide for the detection of **higher harmonics** such as **3F, 4F, 5F** etc., although in all cases the highest harmonic frequency which can be measured is limited to the maximum detection frequency of the lock-in amplifier.

Auxiliary inputs and outputs are often provided so that if the instrument is used under computer control the user can take advantage of the analog to digital converter to digitize other experimental voltages and avoid the need for other instruments or interface cards. Inputs and outputs are usually limited to analog voltages which the user can read or set from the computer, but logic input/output ports are also sometimes provided.

The **ratio mode** usually uses one of these analog inputs to provide the denominator for a ratio calculation, where the numerator is the output from the lock-in amplifier. The lock-in amplifier displays the result of this calculation, which is particularly useful in correcting for source intensity changes in optical experiments. In this type of experiment a separate detector is used to measure the source intensity; the output from it, after amplification, being fed to the auxiliary input.

It has been shown that the output from a lock-in amplifier is a DC signal with an AC fluctuation superimposed on it. The amplitude of this fluctuation is dependent on the noise within a bandwidth defined by the output time constant and centered at the reference frequency. If the AC signal in the output is isolated and rectified then it is possible to measure the level of this noise. The **noise measurement mode**, which is provided on many instruments, performs this function.

Further Information

This Technical Note is intended to describe the specifications used in defining the performance of a lock-in amplifier. Additional information may be found in other PerkinElmer Instruments (Signal Recovery) publications, which may be obtained from your local PerkinElmer Instruments (Signal Recovery) office or representative, or by download from our website at **www.signalrecovery.com**

TN 1000   What is a Lock-in Amplifier?
TN 1002   The Analog Lock-in Amplifier
TN 1003   The Digital Lock-in Amplifier
TN 1004   How to Use Noise Figure Contours
AN 1000   Dual-Channel Absorption Measurement with Source Intensity Compensation
AN 1001   Input Offset Reduction using the Model 7260/7220 Synchronous Oscillator/Demodulator Monitor Output
AN 1002   Using the Model 7220 and 7265 Lock-in Amplifiers with software written for the SR830
AN 1003   Low Level Optical Detection using Lock-in Amplifier Techniques
AN 1004   Multiplexed Measurements using the 7220, 7265 and 7280 Lock-in Amplifier