

THE BENEFITS OF LOCK-IN AMPLIFIERS

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The Benefits of DSP Lock-In Amplifiers

Advances in digital signal processing technology are driving improvements in lock-in amplifier performance.

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If you never heard of, or don't understand, the term "lock-in amplifier", you're in good company. With the exception of the optics industry, where virtually every major laboratory has at least one lock-in amplifier, the majority of people in the fields of science and engineering have never been exposed to lock-in amplifier technology.

That majority is rapidly decreasing. Now that DSP (digital signal processing) technology is being applied to lock-in amplification, the improved benefits of this measurement technique are being realized in more applications than ever before.

Why Use a Lock-In Amplifier?

The measurement of low-level electrical signals is a difficult task. Whether due to 50/60 Hz hum pickup from power lines into a signal cable, $1/f$ noise from high-gain preamplifiers, thermal noise from a sensor, dark current drift from a photodetector, or a combination of the above problems, noise sources of all types and frequencies hamper the ability of typical meters to give a fast, accurate reading at low signal levels.

Whether the measurement is ac or dc, ac noise and dc drift cause the reading to be unstable and increase the uncertainty in the accuracy of the reading.

Long time constants can increase the accuracy of the measurement by averaging out ac noise. However, if the meter itself experiences dc drifts during that time, how valid can the measurement be? Besides, who wants to wait for those long time constants?

Fortunately, lock-in amplification provides a technique for rejecting both ac and dc noise sources before the signal is measured. The measured signal can then be averaged to much shorter time constants, allowing faster and more accurate results.

If there is only one measurement to be made of a signal that does not change significantly with time, it may be acceptable to wait as long as it takes for the signal to settle. However, if there are multiple measurements to be made, those time constants may slow results to a snail's pace.

Consider, for instance, a typical infrared detector with an rms noise level of 10 mV for a one-second integration period, measuring a light level that produces a 100-mV signal. If the desired accuracy of measurement is 1%, then the signal must be integrated over 100 seconds, since the reduction in noise varies with the square root of the integration time. If this measurement were also part of a spectroradiometric scan of 500 data points, the overall scan time would be nearly 14 hours — clearly too long to be of practical use.

When performing the same scan using a lock-in amplifier, most of the noise frequencies are filtered out — reducing the noise by many decades. If, in the above example, the noise was reduced by a factor of 1000, each data point would be obtained at the desired accuracy in 0.1 seconds and the scan time would be less than one minute. This is the basis for using lock-in amplification techniques in most branches of infrared metrology.

Similarly, if the signal to be measured is time-varying, or coincides with some event, it may be missed entirely, or altered in magnitude to the point of irrelevance, if long integration times are used. A case in point is the measurement of the persistence of phosphors. These signals may be of low intensity and decay over just a few milliseconds. To get an accurate measurement using dc methods may be impossible, since noise levels at the short integration times required will generally swamp small signals. Lock-in amplification can reduce noise to levels where measurements are possible.

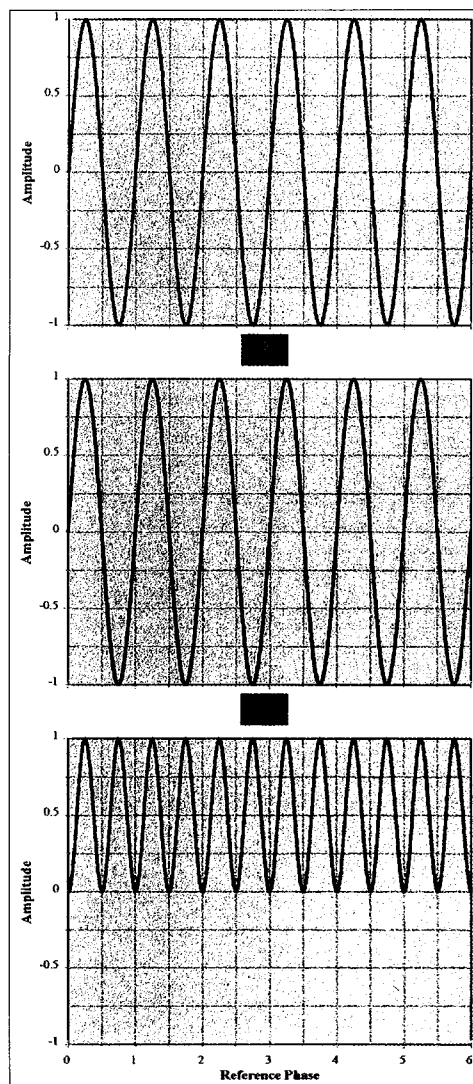


Figure 1. Multiplication of two phase-locked sine waves of identical frequency gives a resultant symmetrical about a dc level.

What is a Lock-In Amplifier?

Lock-in amplifiers have been sometimes referred to as "frequency-selective voltmeters" and "single-channel spectrum analyzers." These descriptions have been used because the devices measure the magnitude of a signal in a very narrow frequency band, while rejecting all components of the signal that are outside that very narrow frequency band. At first glance, this sounds very simple. All that is required is a bandpass filter inserted between the signal source and a voltmeter, but this rarely achieves the desired result. The noise rejection, speed, and accuracy of a good lock-in amplifier surpass what can be done with simple filtering by many orders of magnitude.¹

A lock-in amplifier is capable of measuring small ac signals that are obscured by large amounts of noise. In fact, ac signals can be extracted even when swamped by far greater noise. This ability is the basis for the most common figure of

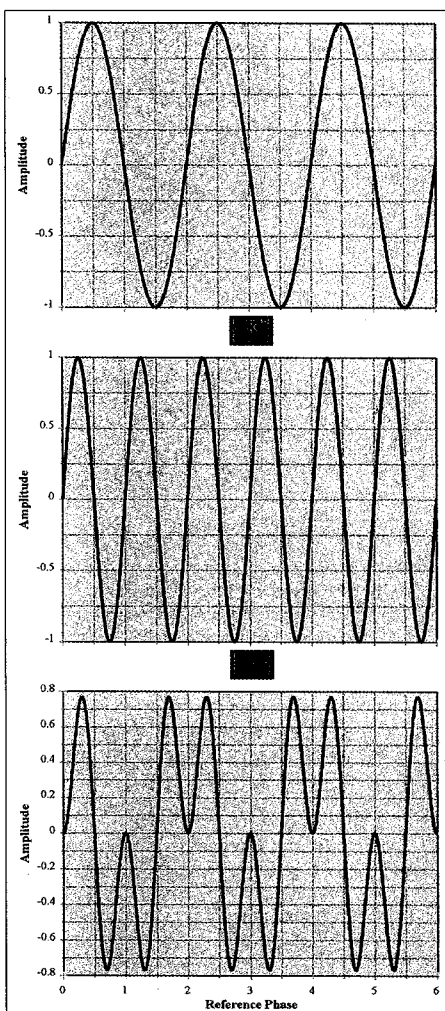


Figure 2. Multiplication of two sine waves of different frequencies gives a resultant symmetrical about zero.

merit used to describe lock-in amplifiers, namely dynamic reserve. Dynamic reserve is usually defined as the maximum noise-to-signal ratio, expressed in dB, that a lock-in amplifier can tolerate while the measurement error is less than 5%. For common analog lock-in amplifiers, this can be up to 60 dB (1000), but DSP-based lock-in amplifiers can achieve as high as 100 dB (100,000) without pre-filtering.^{2,3}

To accomplish this, the lock in amplifier must be provided with a relatively clean reference signal of the same frequency as the signal to be measured.

If the signal to be measured is a dc signal, it must be modulated by an ac waveform either electrically or mechanically. The signal and its modulation frequency (known as a reference signal) can then be fed to a lock-in amplifier.

How a Lock-In Amplifier Works

In a fashion similar to an AM radio receiver, a lock-in amplifier uses a technique known by many names: synchronous detection, auto-correlation, signal mixing and frequency shifting. In lock-in amplifier terminology, this technique is most commonly known as phase-sensitive detection (PSD). Phase-sensitive detection consists of multiplying the input signal by a reference signal of a constant, known magnitude, which is phase-locked to the input reference signal.

Some lock-in amplifiers use a square-wave reference, others use a sine-wave reference. A square-wave reference contains odd harmonics of the fundamental, which cause noise at those harmonic frequencies to be detected. This is usually undesirable.⁴ On the other hand, a perfect sine-wave reference will result in only the fundamental being detected.

The equation for the resultant, Φ , of

multiplying two sine waves is:⁵

$$\begin{aligned}\phi(t) &= V_1 \sin(\omega_1 t) \times V_2 \sin(\omega_2 t + \theta) \\ &= 0.5 \times V_1 V_2 (\cos((\omega_1 - \omega_2)t + \theta) - \cos((\omega_1 + \omega_2)t + \theta))\end{aligned}$$

Equation 1

where:

V_1 is the peak magnitude of the first sine wave, ω_1 is 2π times the frequency of the first sine wave, V_2 is the peak magnitude of the second sine wave, ω_2 is 2π times the frequency of the second sine wave, θ is the phase shift of the first sine wave relative to the second, and t is time.

To illustrate the lock-in amplifier process, Figure 1 shows a signal sine wave multiplied by a phase-locked reference sine wave of the same frequency.

The equation for multiplying these sine waves reduces to:

$$\begin{aligned}\phi(t) &= 0.5 \times V_1 V_2 (\cos(0) - \cos(2\omega t)) \\ &= 0.5 \times V_1 V_2 - 0.5 \times V_1 V_2 \cos(2\omega t)\end{aligned}$$

Equation 2

Since the magnitude of one of these sine waves (the reference) is constant in a lock-in amplifier, if this resultant, $\phi(t)$, is low-pass filtered to remove the $2\omega t$ component, the constant dc voltage remaining is directly proportional to the ac signal being measured.

Signal components that are not of the exact same frequency as the reference will not give this constant dc voltage, since neither the frequency sum nor the frequency difference equals zero. As seen in Figure 2, the resultant for different frequencies is symmetrical about zero so, following low-pass filtering, such components will not contribute to the lock-in amplifier output.

In the case of a dc offset, the lock-in amplifier output component will be the reference frequency times a constant, and will also average out to zero. If the offset drifts slowly, it represents a very low frequency, and will also average out to zero.

Noise components near to the reference frequency will

result in low frequency lock-in amplifier output components. This is due, as seen in Equation 1, to the fact that the frequency difference term in the equation is near to, but not quite, zero. These low output frequencies, commonly referred to as "beats," are more difficult to filter out — requiring long integration times and hence slowing measurements. To avoid low-frequency beats, lock-in users attempt to use a reference frequency that corresponds to a quiet area of the signal's spectrum.

Signal Phase

So far the examples only illustrate the case of a signal whose phase, relative to the reference signal, is zero. When the signal phase is not zero, the output of the lock-in amplifier does not directly represent the signal magnitude. Instead, the relationship varies as $\cos(\theta)$. There are two ways to deal with this:

1. Adjust the phase of the PSD reference versus the input reference until it matches the signal.
2. Perform a dual-phase measurement.

A dual-phase measurement can be performed with a single-phase lock-in amplifier by taking two consecutive measurements, one with the reference phase equal to that of the signal, and one with the reference phase shifted by 90 degrees from that of the signal. With the recorded data, both the signal magnitude and phase can be calculated. This technique assumes that the signal does not change between the two measurements.

A dual-phase lock-in amplifier performs both measurements simultaneously. In a dual-phase lock-in amplifier, there are actually two PSD sections. One PSD operates on a sine-wave reference, and the other operates on a cosine reference (90 degrees from the sine reference). The low-pass filtered dc output of the sine PSD is generally called the X output, whereas that of the cosine PSD is called the Y output.

If the signal is in perfect phase with the reference, the X output is the signal magnitude and the Y output is zero. If the signal is 90 degrees out of phase with the reference, the Y output is the signal magnitude and the X output is zero. But no matter what the phase, the resultant magnitude (V_{out}) of X and Y always represents the signal magnitude.

$$V_{out} = \sqrt{(X^2 + Y^2)} \quad \text{Equation 3}$$

In addition the phase of the signal can be determined by:

$$\theta = \arctan(Y/X) \quad \text{Equation 4}$$

Why is a DSP Lock-In Better?

In an analog lock-in amplifier, the PSD is typically implemented by one of two techniques: sine-wave demodulation or square-wave demodulation.

If sine-wave demodulation is used, the resultant is generated using an analog multiplier. This multiplies the input signal by a sine wave generated by an analog oscillator that is phase-locked to the reference signal.

Although many advances have been made in these devices, errors on the order of 1% and harmonic distortion on the order of -60 dB (0.1%) exist even in "precision" commercially available devices.

If square-wave demodulation is used, an analog switch selects the output of an inverting amplifier stage when the reference is below zero, and a non-inverting stage when the reference is above zero. This technique has the disadvantage of detecting odd harmonics of the reference frequency in the input signal. This means that the user must take great care not only that there is no significant noise in the frequency band near the selected reference frequency, but also that there is no significant noise in the frequency bands near the odd harmonics of the selected reference frequency.

For both analog demodulation techniques, there are gain and offset errors that are not constant with frequency and also drift with temperature and age. There are, in addition, the problems of switching and zero-crossing noise.

The output of either PSD is then fed to an analog low-pass filter to remove the ac components. The low-pass filter has gain and offset errors of its own, which also change with frequency and drift with temperature and age. In addition, the low-pass filter order, time constants, and roll-off slopes are fixed in hardware; cost considerations limit the selection of settings available.

What about DSP lock-in demodulation, in contrast? The amplified signal is input directly to a high-speed, high-resolution A/D converter. The reference oscillator, PSD process,

and low-pass filtering are all done by digital components. A high-quality DSP-generated sine wave contains minimal harmonic distortion and allows the digital PSD to achieve excellent rejection of out-of-band noise. This improved rejection allows a greater dynamic reserve and signal phase-angle accuracy — typically 0.001° with DSP as opposed to 1° obtained with analog lock-in amplifiers.

Assuming that the speed and resolution of the A/D and DSP chips are sufficient, the errors in the digital domain will be negligible and will not drift. Moreover, the DSP low-pass filtering is much more flexible, since it is hardware-independent. So long as the DSP has enough memory and speed, virtually any filter type can be implemented by a change in algorithm and/or filter coefficients. Also, since the PSD is implemented in the digital domain, there is no additional hardware cost involved in providing dual-phase operation.

A Comparison of Results

The relative performance of analog and DSP lock-in amplifiers is easily compared in an electrical testing laboratory. It may be that "top of the range" analog units will give similar results to basic DSP lock-in amplifiers, so in order to provide a like-for-like comparison, two units aimed at the same commercial market were tested.

In these tests, sinusoidal signals of 1 mV and 10 mV at various frequencies were introduced with and without a 500-mV, 60-Hz "noise" component. The output of the lock-in amplifiers with the noise present was divided by that without the noise to provide a measure of noise rejection under difficult, but not unusual, circumstances. Results are shown in Figure 3. As can be seen, the DSP lock-in amplifier gives far superior performance to that of the analog amplifier.

Probably the most significant feature of DSP lock-in amplifiers is that this increase in performance does not increase the purchase price! Over the last decade, the use of DSP technology has grown exponentially. Driven by commercial uses in CD players, cellular phones, and similar consumer electronics, the speed and resolution of DSP and A/D converter ICs are growing rapidly, while the costs are decreasing due to volume production.

These price/performance conditions often make DSP the first choice of most designers who need to handle any kind of analog signal. In electronic measurement equipment, this evolution has progressed from digital multimeters through digital oscilloscopes and in the last five years, DSP lock-in amplifiers.

Since DSP lock-in amplifiers avoid the need for some of the analog components of traditional units, they tend to be more compact. This, in turn, leads to smaller units and often more facilities available such as chopper controllers and PMT high-voltage supplies being incorporated rather than as separate boxes. Also, fully functional PC boards

offering the same, and sometimes superior, facilities of larger traditional stand-alone systems are possible.

The DSP lock-in method does have a limitation, namely, the sampling rate and resolution of the A/D converter and DSP ICs. To avoid dc offset and sampling anomalies, the maximum frequency of operation is limited to half the sampling rate. However, this limit, today typically around 100 kHz, affects only a very small percentage of applications. As the DSP technology progresses, even these very high frequency applications are being accommodated.

Conclusion

DSP lock-in amplifiers provide a cost-effective means of rejecting large amounts of signal noise. They are generally more accurate than analog lock-in amplifiers, especially at lower frequencies, and they do a better job of rejecting noise, due primarily to the fact that they produce less harmonic distortion in the PSD section. They provide more flexibility in terms of filter customization, and their sampling rate/resolution and general signal architecture make them adaptable to different tasks in addition to lock-in amplification. These applications include FFT frequency spectrum measurements, box-car averaging, pulse profiling, and differential and integrating amplification.

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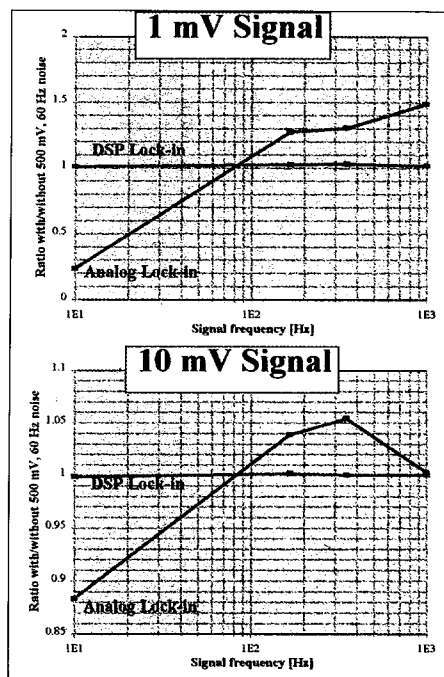


Figure 3. A Comparison of results for analog and DSP lock-in amplifiers with respect to their noise-rejection capabilities.

New DSP Lock-in Amplifiers Can Do More

Over the past few decades, instruments have become much more sensitive. With this increased sensitivity comes all sorts of benefits: ultrasonic scan images of babies before birth; smaller satellite receiver dishes; and cheaper telephone bills to name but a few. Among the great inventions that enabled these benefits to be realized was the lock-in amplifier. Able to separate small signals from large amounts of background noise - similar to hearing a whisper next to a pneumatic drill - the lock-in amplifier is responsible for many modern innovations.

Although lock-in amplifiers are found in many devices, it is a term not generally recognized. Most major electrical or optical laboratories will have one, but for the most part they are hidden within the inner workings of chemical, pharmaceutical, medical and other scientific equipment.

Now lock-in amplifiers are themselves undergoing a revolution. As old analog parts are replaced by digital signal processing (DSP) devices, the sensitivity can be increased by hundreds of times - like hearing the whisper next to a jet aircraft taking off. With this increased sensitivity, it is only a matter of time before all those "hidden" lock-in amplifiers are replaced, improving the performance of a wide range of instruments.

Optronic Laboratories, Inc. has developed two exciting new DSP lock-in amplifiers: the OL 730D is a stand-alone dual-phase lock-in amplifier suitable for almost all electrical and optical laboratory or process control applications; and the OL 4000 is a versatile PC-based plug-in board aimed at OEM developments. Each is part of a complete package, offering everything required from signal preamplifiers to output filtering and, naturally, all parameters are programmable.

One especially useful feature of DSP lock-in amplifiers is they are more compact than their analog counterparts. This allows a unit of the same size to do much more than was previously possible. The OL 730D, for instance, incorporates optional PMT high

voltage and low voltage biasing for other optical detectors, power supplies for coolers and optical chopper driver circuits inside the lock-in's housing or integrated modules. The OL 730D is no bigger than many laptop computers, saving valuable work space.

amplification are just a few examples of the other possible applications of the OL 730D.

The OL 4000 PC-based plug-in board offers many of the features of the OL 730D. Aimed primarily at OEM markets, it was developed

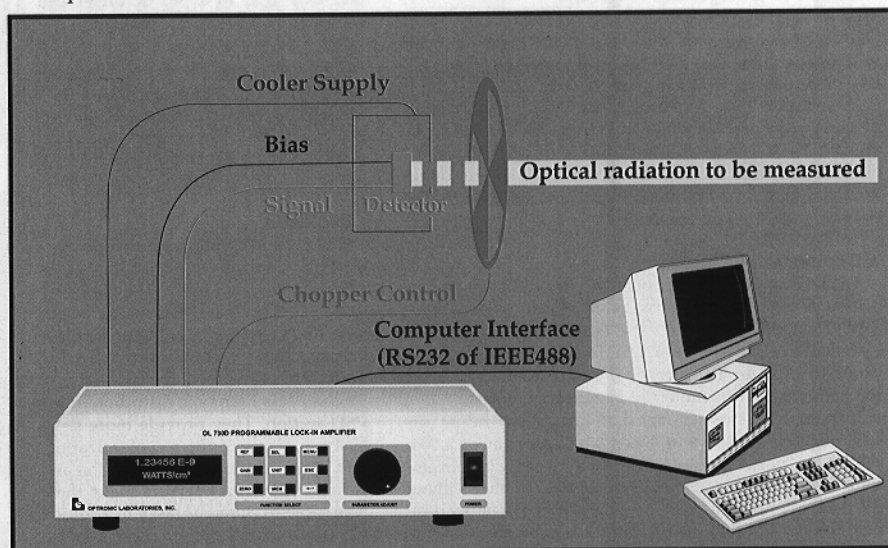


Figure 1. The OL 730D lock-in amplifier features many facilities for optical radiation detection, previously only available in multiple units, saving both space and money.

Although the OL 730D offers all the features expected of a high quality lock-in amplifier, with these extra facilities it becomes a radiometer capable of interfacing any optical detector. Special firmware within the unit, and an easy to use keypad provide full photometer/radiometer functionality.

Impressive as these features are, they are really just the tip of the iceberg, because the OL 730D is more than a lock-in amplifier or a radiometer. Also provided as standard are DC and photon counting modes of operation, and with the prodigious on-board memory any waveform or event can be captured and analyzed. Pulse profiling, single and dual beam ratios, integrating and differential

to meet the needs of most manufacturers. It can be supplied in various configurations to suit a wide range of applications. Special general purpose preamplifiers are available to recover the smallest of signals; and a complete developer's kit provides programmers with the necessary drivers and examples.

Optronic Laboratories, Inc. has been established for 26 years and, through high quality of design and manufacture, enjoys a worldwide reputation for excellence in many fields of instrumentation and measurement.

**Introducing the OL 730D and OL 4000
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