EG&G PRINCETON APPLIED RESEARCH

Scientific Instrument Group

"...The leaders in Signal Recovery."

Explore the Lock-In Amplifier

With it, you can measure the ultra-low distortion components of a "linear" signal, and at super-high effective Qs.

If you have to measure distortion components with relative magnitudes of 100 ppm or less-or if you can't use excitations of greater than 10 mV in distortion testing— the lock-in amplifier may provide the solution.

With it, you can do the following:

- Measure weak distortion components in the presence of obscuring background noise.
- Measure directly the distortion of a linear system without concern for the spectral purity of the excitation sources.

Of course, the lock-in amplifier has limitations, too— chiefly the frequency range, which is limited to 0.1 Hz to 200 kHz.

Other instruments also measure distortion—for example, the total-harmonic-distortion (THD) meter and the wave analyzer. But the lock-in can do what each of these does-and at ultra-low levels.

The THD meter operates by notching out the strong fundamental and measuring the weak residuals with a broadband detector, while the wave analyzer measures the intensities of specific harmonics, from which the THD can be computed.

To do this, the device under test is excited with a sinusoid, and a narrowband analyzer measures the harmonics. As distortion decreases, more analyzer gain is needed. But as gain is increased, the equivalent noise bandwidth must be narrowed to avoid overload from related harmonics, power-line pickup, random noise and even the fundamental.

Thus frequency stability becomes critical and what's needed ideally is a driftless, super-high-Q analyzer: enter the lock-in.

How it works

The name "lock-in amplifier" suggests to many engineers a tracking filter or phase-locked oscillator. However, it would be more appropriate to liken the lock-in to a synchronous demodulator or phase-sensitive detector.

Actually, the lock-in is a specialized ac voltmeter that uses synchronous demodulation to measure signal strength or phase, even under severe noise conditions—that is, where the noise-to-signal ratio approaches 130 dB. Full-scale sensitivities of 10 nV or 0.1 pA are typical. The instrument can be used wherever the signal of interest can be synchronized with or derived from a suitable reference signal.

The output of the lock-in—a phase-sensitive dc voltage proportional to the signal—is available for recorders or for further processing. Or it can serve as a control signal in a servo feedback-loop system.

The lock-in can be divided into four main sections: a signal channel, reference channel mixer (phase-sensitive detector] and dc amplifier/low-pass filter (Figure 1).

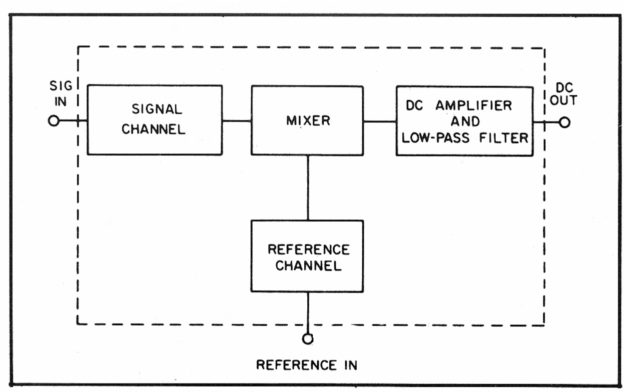

FIGURE 1. Basically the lock-In amplifier detects weak signals by the process of synchronous demodulation. Extraneous signals, which are not synchronized to the reference, are rejected.

In the signal channel, the input signal (and noise) is conditioned by the low-noise preamplifier and post-amplifier, with a filter sandwiched in between. The filter can be a tunable bandpass, notch, low or high-pass network. Sometimes it's referred to as a predetection filter, since its purpose is to reduce the possibility that the mixer will overload during severe noise conditions. However, the biggest improvement in signal-to-noise is contributed by the mixer and dc-amplifier/low-pass filter sections, and not the predetection filter.

The reference channel transforms the externally applied reference to a suitable square wave (at the reference frequency) to drive or switch the mixer, the lock-in's output is independent of the reference amplitude, as long as the reference exceeds a specified threshold—typically 100 mV.

However, the output does depend on the phase difference between the signal and the reference. Since the phase difference is usually unknown, a manually control-able 0-to-360° phase shifter is incorporated into the reference channel to facilitate signal-level measurements. Some lock-in amplifiers have an f/2 mode to permit the mixer to be driven at twice the reference frequency—a useful feature for second-harmonic measurements, for example.

You may wonder how, or where, to get a reference— and to get it synchronized to the signal, no less. If you think of an ac-bridge balancing application—where the bridge excitation Is the reference and the null is the signal of interest—it's apparent that a lock-in amplifier is really an extremely sensitive null detector.

Mixer is the key stage

Often referred to as a phase-sensitive detector or synchronous demodulator, the mixer stage is actually the heart of the lock-in instrument (Figure 2). The mixer can be thought of as an electronic reversing switch whose sense or position is determined solely by the square-wave drive polarity. Thus the signal-channel output is commu-tated at the reference frequency.

There are two basic ways to analyze the demodulation process—graphically and mathematically. In the graphical, the signal-channel output consists of two equal-amplitude sinusoids—one in and the other out of phase with the reference. During the first half cycle the reference drive is positive and the switch in Figure 2 is in position A. The mixer output is a positive, half-wave sinusoid during this interval. During the second half cycle the switch is in position B, but the mixer output is still positive.

Clearly, when the reference and sinusoidal signals are in phase at the mixer input terminals, the mixer output is a full-wave rectified sinusoid whose fundamental is twice the reference frequency and whose dc component is proportional to the signal of interest. When the reference drive and signal are in quadrature—that is, their phase difference 4> is 90°—there is no dc component. In general, the dc component is phase-sensitive—it varies as the cosine of </>.

When the reference is not synchronous with the signal channel output (as in the case of noise), though ac fluctuations exist, there will be no dc component regardless of the reference-channel

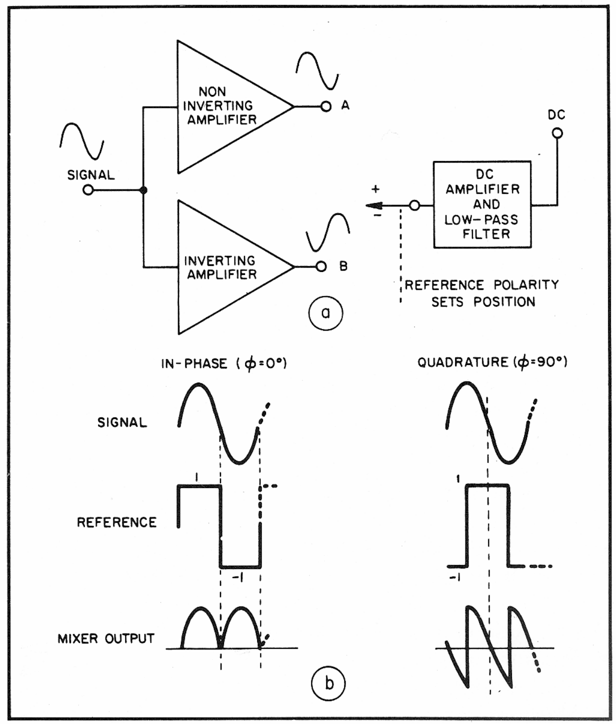

FIGURE 2. Key element of the lock-in is the mixer, which operates as a phase-sensitive switch (a). The switch position depends on the polarity of the reference square wave drive, so that the input signal is commutated at the reference frequency (b).

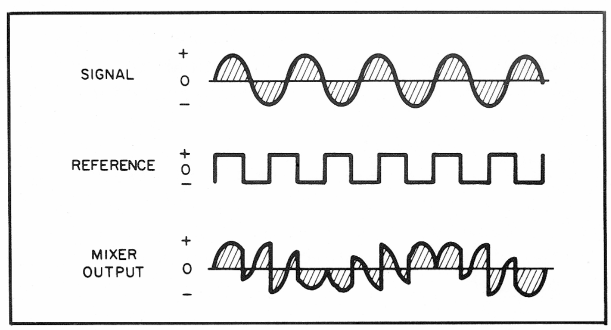

FIGURE 3. When the signal isn't synchronized with the reference, as in the case of noise, the average (dc) level of the mixer output is zero.

In the mathematical analysis of the demodulation process, the mixer output, m(t), can be thought of as the product of the signal-channel output s(t), and a ±1 V pk-pk square wave. With the reference represented by a Fourier series, m(t) may be written as:

$$m(t) = \sum_{n=0}^{\infty} s(t) \frac{4}{(2n+1)\pi} \sin[(2n+1)\omega t + \phi_n]$$

If s(t) has a frequency component in common with any of the *reference* components (usually only the fundamental), there will be a phase-sensitive dc component. Note that ac components will always exist, composed of sum and difference frequencies of the signal and all the reference Fourier components. If </>$_n$=0, and s(t) is sinusoidal, the expression for m(t) is the Fourier-series expansion of a full-wave rectified sine wave.

Actually, the signal to be measured is usually somewhat more complex—such as the square or trapezoidal waveforms found in photometry, where the signal is derived from *a* mechanical or electro-optical chopper. However, by the time such a signal reaches the mixer, its appearance is nearly sinusoidal, depending on the type of predetection filtering used.

Noise makes no contribution

Nonsynchronous inputs (noise) share no common frequencies with the *reference* and will not contribute dc components to the mixer output. When the mixer output is passed through a low-pass filter to remove the ac fluctuations, the signal to noise (dc/ac) is enhanced in proportion to the square root of the filter time constant.

The final section of the lock-in—the low-pass filter and de-amplifier combination—amplifies the dc component of the signal and attenuates the ac components. The attenuation depends on the frequencies, the low-pass filter time-constant (T)—usually 1 ms to 300 s—and the number of filter sections used. A choice of — 6 dB/octave or — 12 dB/octave is usually available.

Since the equivalent noise bandwidth (ENBW) is determined by the low-pass filter and not the signal-channel filter, bandwidth can be extremely narrow. For single and double-section filters, ENBW equals 1/(4T) and 1/(8T), respectively. Thus a 300 s time constant at — 12 dB/oct rolloff rate gives an ENBW = 0.00042 Hz.

In the distortion measurement in Figure 4, the lock-in amplifier is used to detect a 1.4 kHz signal with a time constant setting of 1 s at a —6 dB/oct attenuation rate.

Since the noise-induced fluctuations of the meter are acceptably small, no further filtering is needed. These figures correspond to an output bandwidth of 0.159 Hz. If system Q is defined as the center frequency divided by the 3 dB bw, the lock-in amplifier Q is approximately 8700—a super-narrow band by any definition.

Details of the measurement are as follows.

Suppose you want to measure the second harmonic generated in the signal channel of a typical lock-in with a plug-in preamplifier; the lock-in amplifier thus serves as both the system under test and the analyzer (Figure 4).

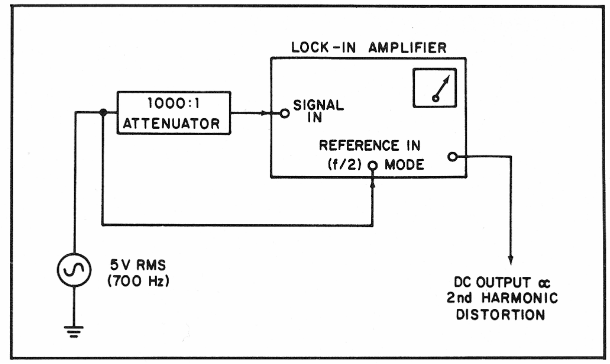

FIGURE 4. To measure the second harmonic distortion generated in an amplifier (in this case, the lock-in itself), this test setup is used.

A low-distortion oscillator, set to 700 Hz, serves as both the lock-in amplifier *reference* and, with a 1000:1 attenuator, the 5 mV input to the preamp. With the *reference* channel mode switch in the f/2 position, the lock-in amplifier responds to only 1400 Hz.

The signal-channel notch mode (predetection filter) is used to attenuate the fundamental by nearly 80 dB. This reduces the likelihood of mixer overload as the sensitivity is increased. An oscilloscope connected to the monitor output connector (premixer) helps adjust the notch for maximum effectiveness.

With this configuration, a 130 nV rms signal is measured on the 200 nV full-scale range. This corresponds to 26 ppm of the second harmonic. How much of this is contributed by the excitation source? To determine this, an alternate method can be implemented—one that doesn't require the excitation source to be stringently pure (Figure 5).

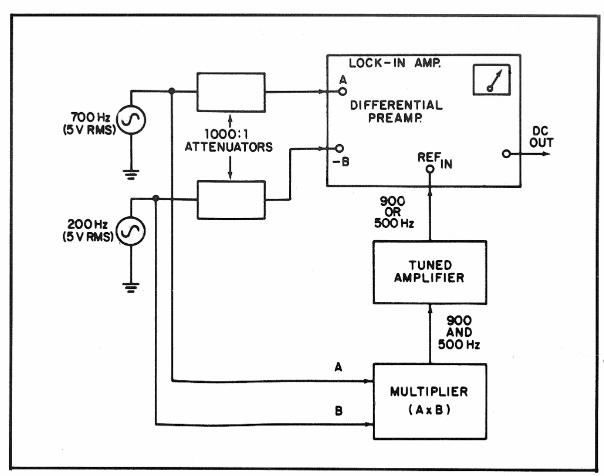

FIGURE 5. Intermodulation products can be measured with a differential preamp in the lock-in's front end. Harmonic distortion can then be calculated from the measured products. In this way the spectral purity (impurity, actually) of the excitation source can be neglected.

Excitation source isn't critical

In this method two 5 mV rms uncorrelated sinusoidal sources are applied differentially via the plug-in preamp to the signal channel. The signal channel output, E_0 (disregarding predetection filtering), can be determined by substitution of $E_i = A\,(\cos x + \cos y)$ in the power-series expansion:

$$E_0 = K_1E + K_2E^2 + K_3E^3 + \ldots \qquad (1)$$

where Eι = the input voltage, K_1 = signal channel gain, and the remaining Ks = distortion constants. Since the measurement deals with ultra-low distortion effects and small excitations, higher order terms are neglected.

The response consists of many ac components: each fundamental, respective harmonics and intermodulation products $ax \pm by$, where $1 \le a \le 2$ amd $1 \le b \le 2$. Thus

$$E_o = K_1A(\cos x + \cos y) + K_2A^2[1 + \frac{\cos 2x + \cos 2y}{2}] +$$
$$\cos(x+y) + \cos(x-y) + K_3A^3[\frac{\cos 3x + \cos 3y}{4}] + \qquad (2).$$
$$9/4(\cos x + \cos y) +$$
$$3/4]\cos(y+2x) + \cos(y-2x) + \cos(x+2y) + \cos(x-2y)]$$

To determine the system's second-harmonic distortion, measure either of the intermodulation products (x + y) or (x — y) without worrying about the purity of either excitation source.

The useful relationships between harmonic distortion and the intermodulation products are obtained when Equation 1 is expanded for a single input ($E_i = A\cos x$), and then compared with the two-input expansion (Equation 2).

When this is done, the second harmonic distortion then equals one half the magnitude of the intermodulation component at frequency x + y (or x - y), divided by the magnitude of the fundamental.

Similarly, the third-harmonic distortion equals one third the magnitude of the intermodulation component at frequency ax + by (or ax —by), divided by the magnitude of the fundamental. Therefore:

$$\text{2nd harmonic distortion} = \frac{K_2A}{2K_1}$$

$$\text{3rd harmonic distortion} = \frac{K_3A^2}{4K_1}$$

where $a \ne b \ne 0$.

With a measured 120 nV at both the sum and difference frequencies (700 ±200 Hz), the second-harmonic distortion is $1/2 \times 120 \times 10^{-9}/5 \times 10^{-3}$, or 12 ppm. It can be claimed that the oscillator contributes 130-60 = 70 nV of second harmonic, well within the manufacturer's specifications. The assumption made here is that the second harmonics generated by the oscillator and lock-in are in phase at the signal-channel output. The signal chann

predetection filter is placed in the bandpass, rather than notch, mode because two strong components are present at 700 and 200 Hz.

To obtain the lock-in amplifier reference drive, multiply the oscillator outputs and tune the selective amplifier to the desired frequency, 500 or 900 Hz. Similarly, you can find the third harmonic distortion by measuring one of the intermodulation components associated with the K_3 coefficient—that is, the (y + 2x) term. This requires an additional multiplier (squarer) to obtain a suitable reference.

The results should not imply that 12 ppm is the measurement limit. Actually, one to two orders of magnitude less distortion can be measured with the lock-in method. Typical applications are shown in Figure 6.

Note that in some cases no external generator is needed since the lock-in's internal oscillator serves as both the reference and excitation source.

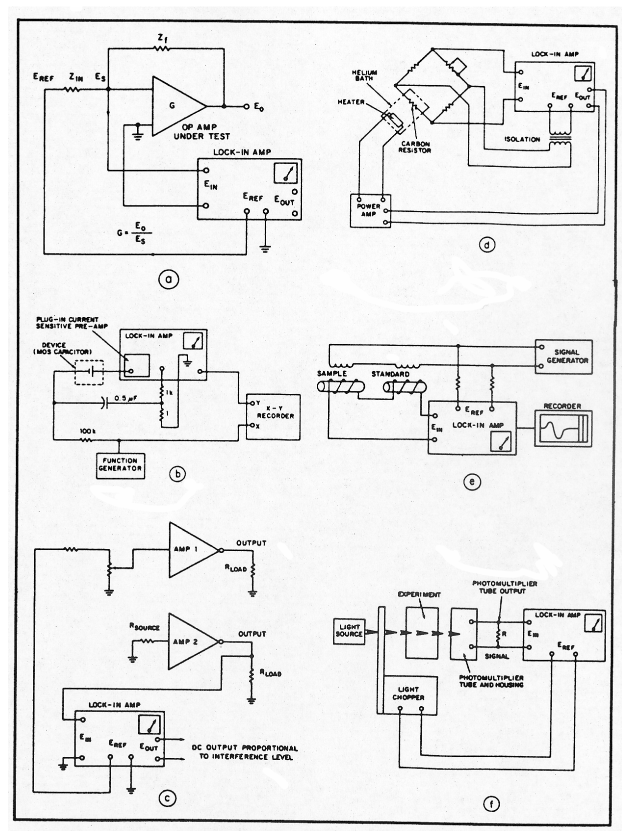

FIGURE 6. In typical applications, the lock-in is used to measure the open-loop gain of an op amp (a); to determine the C-V (capacitance-voltage) characteristics of an MOS semiconductor (b); and to measure amplifier crosstalk (c). But the lock-in's versatility is demonstrated by its use as a temperature controller (d), eddy-current tester (e), and photometric Instrument (f). In some cases, the lock-in's oscillator acts as reference and excitation.

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P.O. BOX 2565 • PRINCETON, NJ 08540, U.S.A. • 609/452-2111 • TELEX: 843409
TN115: 38/2-M5

Printed in U.S.A.