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Digital lock-in amplifier based on soundcard interface for physics laboratory

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Abstract. The purpose of this paper is to develop a digital lock-in amplifier based on soundcard interface for undergraduate physics laboratory. Both series and parallel RLC circuit laboratory are tested because of its well-known, easy to understand and simple confirm. The sinusoidal signal at the frequency of 10 Hz – 15 kHz is generated to the circuits. The amplitude and phase of the voltage drop across the resistor, R are measured in 10 step decade. The signals from soundcard interface and lock-in amplifier are compared. The results give a good correlation. It indicates that the design digital lock-in amplifier is promising for undergraduate physic laboratory.

1. Introduction

The lock-in amplifier (LIA) is a versatile instrument used extensively in laboratory research, especially in condensed matter physics [1-5], that demonstrates aspects of both the science and the art of precision electronic measurements. Experimental physicists are frequently faced with the challenge of measuring extremely small electronics signals from any number of sources under high noisy environment. In this research, we have implemented a PC-based soundcard as lock-in amplifier completely in software. It is both a powerful measurement device and a useful tool for teaching the basics of lock-in detection. We use the LIA to measure the RLC series circuit as it undergoes its resonance condition. As it is a versatile device, it may be applied to any experiments which requires detection of a small (less than a microvolt), slowly varying (stable over several seconds) voltage that is in response to and externally applied voltage: the Hall Effect in semiconductors, the thermistor bridge to detect small temperature changes, and many other example from physics and engineering.

2. Theoretical background and experimental description

2.1 Overview of Lock-in detection

The ideal lock-in amplifier is based on the cross-correlation signal detection. It is a kind of device which adopts Cross-correlation calculation between the detected signal and the same frequency reference signal detection [8, 9]. Due to various signals component is included in the detected signal, the lock-in amplifier adopts heterodyne oscillation technology, transforming the signal component which same as the reference signal frequency into the DC signal, while the other frequency components are converted into AC signal, filtered by the low-pass filter. Accordingly, the lock-in amplifier applies phase-sensitive detection (PSD) to detect the same frequency component between the signal containing noise and the reference signal. The principle of LIA is shown in Figure 1.

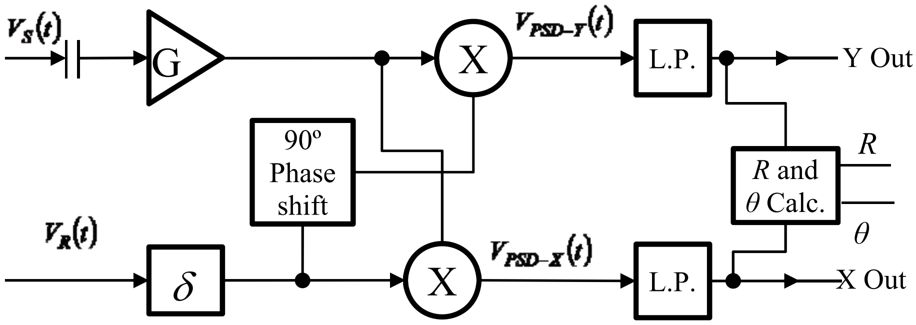

Figure 1. Block diagram of phase-sensitive detection (lock-in detection).

The figure 1 illustrates how the lock-in works, the input signal $V_S(t)$ pass through a capacitor, blocking any DC offset, and is then amplified (G). The reference signal $V_R(t)$ passes through an adjustable phase shifter (δ). This reference will split in 2 part as in-phase (*X*-component) and 90º out of phase (*Y*-compoenent). These two results are then multiplied in separate PSD, and any result in DC component is extracted by the low-pass (L.P.) filter. The filtered result V_{PSD-X} and V_{PSD-Y} can use to calculate the amplitude (*R*) and the phase (*θ*).
We assumes that the signal of interest is centered on a frequency ω_S which is present in the input signal to the PSD.

$$V_S = A_S \sin(\omega_S t + \delta_S) \tag{1}$$

This signal is then multiplied/mixed by a reference for the *X* and *Y* channels of the lock-in:

$$V_{RX} = \sin(\omega_R t), \quad V_{RY} = \cos(\omega_R t) \tag{2}$$

to form the "unfiltered" *X* and *Y* channel output of the V_{PSD}:

$$V_{PSD-X}(t) = V_S(t) V_{RX}(t), \quad V_{PSD-Y}(t) = V_S(t) V_{RY}(t) \tag{3}$$

Here, δ_S is the phase of the input signal of frequency ω_S with respect to the reference signal, and A_S is the amplitude of the input signal with frequency ω_S. To understand the effect of mixer, we rely on the trigonometric identities:

$$\sin(A)\sin(B) = \tfrac{1}{2}[\cos(A-B) - \cos(A+B)] \tag{4}$$

$$\sin(A)\cos(B) = \tfrac{1}{2}[\sin(A+B) + \sin(A-B)]\,. \tag{5}$$

Application of these identities yields:

$$V_{PSD-X} = V_S V_{RX} = \tfrac{1}{2} A_S[\cos((\omega_S - \omega_R)t + \delta_S) - \cos((\omega_S + \omega_R)t + \delta_S)] \tag{6}$$

$$V_{PSD-Y} = V_S V_{RY} = \tfrac{1}{2} A_S[\sin((\omega_S + \omega_R)t + \delta_S) + \sin((\omega_S - \omega_R)t + \delta_S)] \tag{7}$$

In most experimental situations, the signal is close in frequency to the reference: $\omega_S - \omega_R << \omega_R$ and $\omega_S + \omega_R \approx 2\omega_R$. For the case $\omega_S = \omega_R$, we have $\omega_S - \omega_R = 0$ and $\omega_S + \omega_R = 2\omega_R$, then the unfiltered V_{PSD-X} and V_{PSD-Y} outputs contain a rapidly oscillating term superimposed on a time-independent one:

$$V_{PSD-X} = V_S V_{RX} = \tfrac{1}{2} A_S[\cos\delta_S - \cos(2\omega_R t + \delta_S)] \tag{8}$$

$$V_{PSD-Y} = V_S V_{RY} = \tfrac{1}{2} A_S[\sin\delta_S + \sin(2\omega_R t + \delta_S)] \tag{9}$$

By the use of low-pass filter, we can filter the AC component and retain the DC component. The low-pass filter output signal is:

$$X = V_{PSD-X}\big|_{filtered} = \frac{A_S}{2}\cos\delta_S, \quad Y = V_{PSD-Y}\big|_{filtered} = \frac{A_S}{2}\sin\delta_S \tag{10}$$

or

$$A_S = 4\sqrt{X^2 + Y^2}, \quad \delta_S = \arctan(Y/X)\,. \tag{11}$$

By the equation (8) – (11), when input signal and the reference are no phase difference, the lock-in amplifier can accurately measure the magnitude of the input signal. When the phase difference is non-zero, the lock-in amplifier can be used to determine the phase difference between input signal and the reference signal. Thus, by appropriately adjusting the lock-in amplifier parameters, it can accurately obtain the amplitude and phase of the input signal, and also the corresponding frequency of the signal. This idea is simple enough, but the actual implementation is difficult and commercial lock-in is expensive (~5,500USD).

Modern personal computer processor unit is fast also included with digital input/output soundcard. One can use ADC part from the soundcard as input for digital lock-in amplifier and using some skill in programming to do the digital signal processing part as multiplier and low-pass filter for the digital data. Also with the feature of graphic user interface, it also possible to do real-time display and analyze data on the same computer. For the detail of programming will not present in this paper.

2.2 The sound card digital lock-in amplifier

2.2.1 Front panel of digital lock-in amplifier The graphics user interface (GUI) of the digital lock-in amplifier based on soundcard is divided in to a signal generation panels, numeric output signal extraction with the plot panels and the control parameter of the lock-in amplifier. The signal generation panel is composed 2 set of the dropdown menu for waveforms select, frequency knob, amplitude knobs, phase number input and reset button. Control parameters of the lock-in amplifier panels composed input for type of low-pass filter, time constants, filter roll-off point in dB, the order and phase shift of the reference. Signal extraction panel is composed of numeric display for measured values output (X, Y, R, θ and frequency). The designed front panel of digital lock-in amplifier is shown in Figure 2.

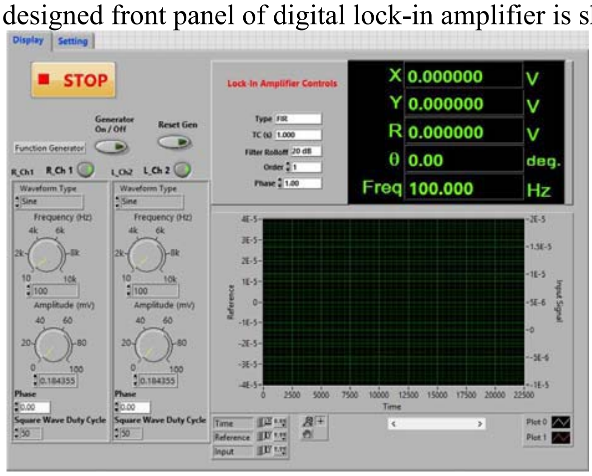

Figure 2. GUI front panel of Digital lock-in amplifier based on soundcard.

2.2.2 Digital lock-in amplifier block diagram. Shown in Figure 3 is the block diagram of digital lock-in amplifier, it is composed of (1) the soundcard configuration modules, (2) the signal generators module, (3) the phase-sensitive detection module, (4) the signal recovery or low-pass filter module, (5) the measured value display module and (6) the program process control module which running in background.

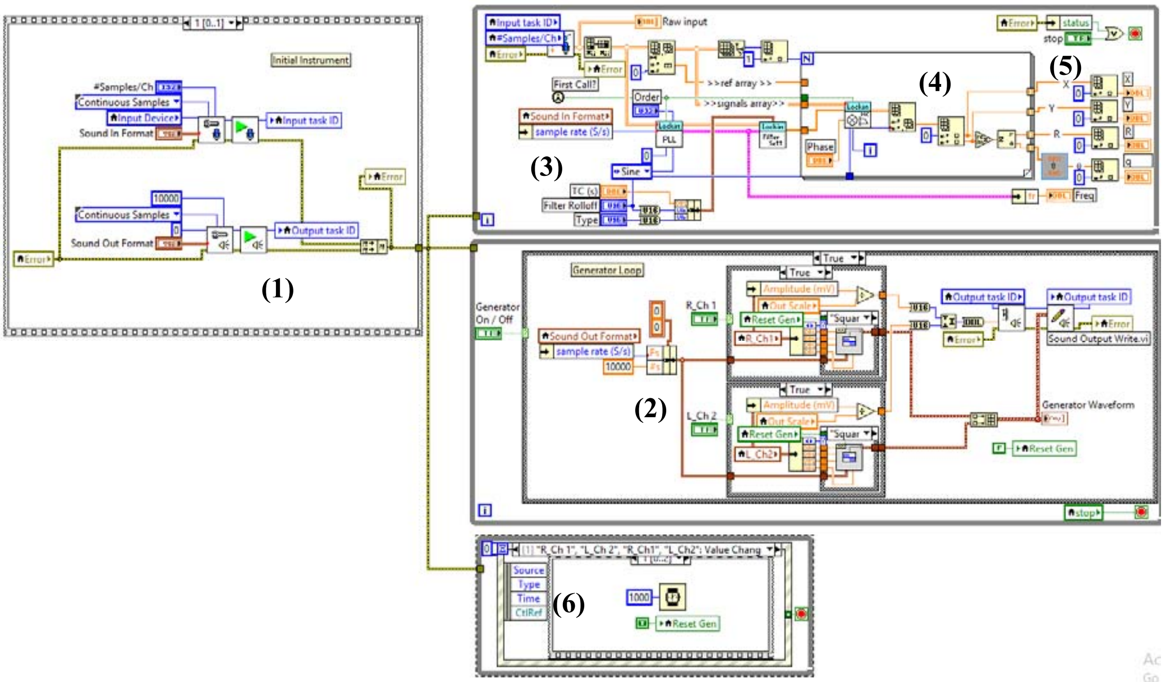

Figure 3. LabVIEW block diagram of the digital lock-in amplifier

2.3 Series RLC circuit measurement

Most undergraduate physics student have learned that the series RLC circuit shown as schematic in Figure 4. The component have very different phase relationships to each other when connected to a sinusoidal AC voltage sources. The basic concept of the RLC circuits are well explained in most electronics textbooks [10] and physics textbooks [11]. By using PC sound card as lock-in amplifier one can measure the frequency response for the series RLC circuits in the range of frequency about 10 Hz – 10 kHz, which is limited by the sound card specification but still cover by the bandwidth of the general PC soundcard, by measure the voltage drop over the resistor in series RLC circuit. The expression for response of voltage drop over resistor R as a function of the sinusoidal waveform input with frequency ω_R represent as:

$$V_R = V_0 R\left[R^2 + (\omega_R L - 1/\omega_R C)^2\right]^{-1} \quad (12)$$

and the phase difference is:

$$\theta = \arctan\left[\left(\omega_R L - (\omega_R C)^{-1}\right)R^{-1}\right] \quad (13)$$

And the resonance frequency for RLC can be defined as:

$$\omega_0 = (LC)^{-1/2} \quad (14)$$

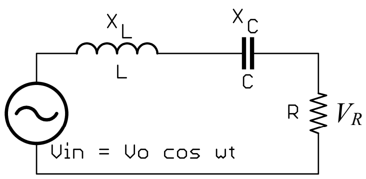

Figure 4. Series RLC filters circuit connected to the sinusoidal voltage source $V_{in} = V_0\cos\omega t$

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2.4 Experimental setup

The diagram of experiment setup by commercial lock-in amplifier SR830 shown in Figure 5 and measure by soundcard lock-in amplifier shown in Figure 6. The value of the component used in the series RLC circuit shown in Figure 5 and Figure 6 as resistance $R = 100\Omega$, inductance $L = 35\text{mH}$ and the capacitance $C = 1\mu\text{F}$. Using the inductance and the capacitance value one can calculate the resonance frequency of the RLC circuit as $\omega_0 = 850.72\text{Hz}$.

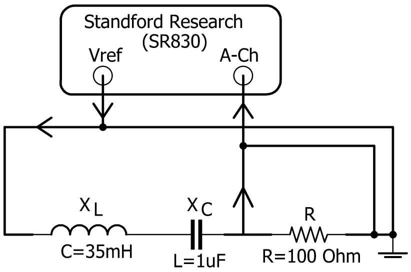

Figure 5. The diagram of frequency response measurement for the series RLC circuits by commercial lock-in amplifier from Standford Research model SR830.

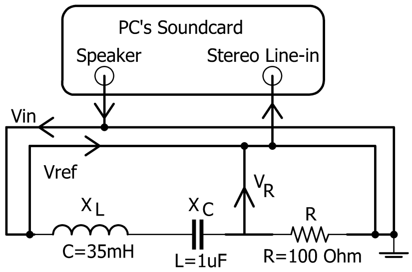

Figure 6. The diagram of frequency response measurement for the series RLC circuits by commercial lock-in amplifier from Standford Research model SR830.

3. Result

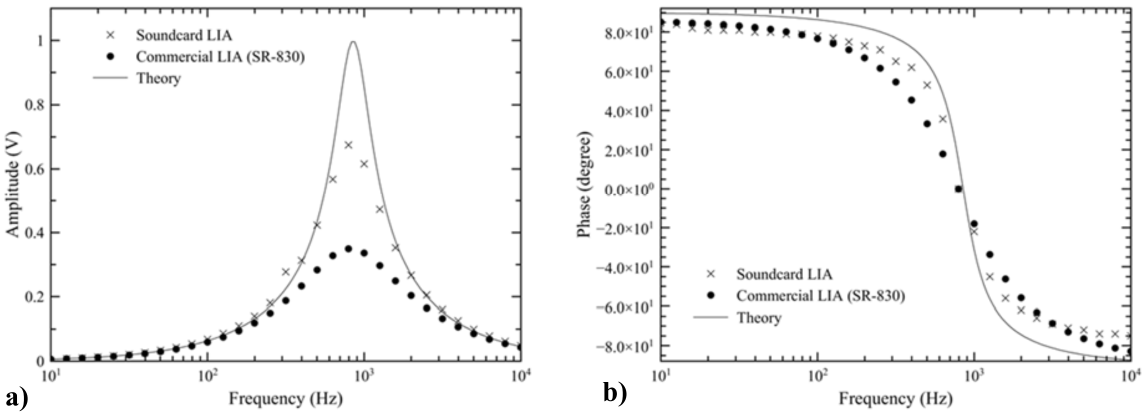

Figure 7. The left plot a) shows a signal amplitude as a function of frequency for the series RLC circuit measure by soundcard lock-in amplifier (cross mark, x) compare to the commercial lock-in amplifier on the same circuit (dot, ●) and theory (line,-). The right plot b) shows a phase signal as a function of frequency for the series RLC circuit measure by soundcard lock-in amplifier (cross mark, x) and by the commercial lock-in amplifier on the same circuit (dot, ●) and theory (line,-).

Since a lock-in amplifier is a sensitive AC voltmeter, which give the information of both amplitude and phase of the measurement signal compare to the pure sinusoidal waveform reference at the specific frequency. Hence the current and a function of frequency for the series RLC circuits can be determine by measure the voltage drop across the resistance in the circuit. We have set the frequency to the 10 step per decade from 10 Hz to 10 kHz. The Figure 7 show the signal of amplitude and phase, figure 3 a) and b) respectively, as a function of frequency which measure by soundcard lock-in amplifier (x) and the commercial lock-in amplifier Stanford Research Systems model SR830 DSP (-). The result clearly shows the signal look almost the same, even signal from the soundcard can give better quality factor may be due to the fact of higher digital resolution (16-bits ADC in soundcard, 8-bits ADC in SR830).

4. Discussion

The purpose of this research is to introduce the students to the idea of using PC soundcard as digital lock-in amplifier. Although we discussed a series RLC circuits experiment, it would be straightforward to adapt the soundcard-LIA to any small signal that may be periodically modulated. It is also low-cost for the equipment required (computer, soundcard, and homemade amplifier) is readily available and is used for many different experiments. The program not only replaces the lock-in amplifier but also handle the real-time plot record and analyse charts data. It is quite sensitive, and its sensitivity can be further improved with an inexpensive input amplifier and ADC. Its shows the advantage over a commercial unit and using as a teaching tool in undergraduate level at the reasonable cost. The software can implement more powerful to simulation capabilities: not only the LIA but also can simulate the entire experiment. In fact, in order to acquaint the students with the software and lock-in amplifier functional, we can assign each student a partial simulation to complete before the experiment. That mean, we can not only place a lock-in analyser on every PC in our lab, we can give each student to take home. These feathers make the PC-based digital lock-in analyser an excellent tool for the 2nd or 3rd year physics lab.

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