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A Weak Signal Detection System: Design and Simulation

Tingxuan Hu
School of Automation Engineering
Qingdao Technological University
Qingdao, Shandong
266000, China

Dong Zhang*
School of Automation Engineering
Qingdao Technological University
Qingdao, Shandong
266000, China

Jianhe Lei
School of Automation Engineering
Qingdao Technological University
Qingdao, Shandong
266000, China

Qiang Wei
School of Physics and Electronic Engineering
Taishan University
Tai'an, Shandong
271021, China

***Abstract* – In many cases, the signal of interest is obscured by noise. Noise such as the inherent noise of system and the interference of the external environment is inevitable, so a weak signal detection system is designed in this paper to solve the de-noising problem in strong noise backgrounds. The core of the system is a dual-phase lock-in amplifier based on an analog multiplier. Lock-in Amplifier (LIA) has the advantages like stable center frequency, narrow band-pass, high quality factor and so on. Simulation way (using MATLAB/SIMULINK) is adopted in this paper to show the effect of the weak signal detection system based on LIA, and then the TINA software is used to help hardware design. Simulation experiments results show that the method proposed in this paper works well.**

Keywords* – *weak signal detection system, de-noising problem, lock-in amplifier, simulation

I. INTRODUCTION

The technology of weak signal detection is widely used in radar, communication, sonar, earthquake and industrial measurement [1]. Weak signal has two meanings: the useful signal amplitude is relatively weak to the noise, or the useful signal amplitude itself is very weak [2]. In signal processing, noise (such as the inherent noise of system and the interference of the external environment) is inevitable [3]. Compared with noises, the amplitude of the useful signal is weak and completely obscured by the noise [4]. So, extraction of weak signal under strong noise background is an important content of the signal processing [5].

At present, lock-in amplifier (LIA) is widely applied in weak signal detection system designation, and has a very strong anti-noise performance [6]. This paper focuses on the simulation method of LIA design to try to improve the Signal-Noise Ratio (SNR). The software of TINA and MATLAB/SIMULINK are used to verify the performance of the designed system.

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Dong Zhang is the corresponding author.
E-mail:anthony1979@qq.com.

II. THE METHOD OF LIA

The detection principle of the orthogonal vector lock-in amplifier is the cross-correlation detection. In essence, LIA can not only transfer the signal spectrum by using phase sensitive detection but also restrain noise and filter the high-frequency component by using low-pass filter as well. The system structure diagram is depicted in Fig.1. The system consists of four parts, including the signal channel, the reference channel, the phase sensitive detection (PSD) and the low-pass filter (LPF).

There is a need of two PSDs in the orthogonal vector lock-in amplifier. In phase channel PSD1, the phase of reference input is $\theta(0\sim360°)$; and the phase of reference input is $(\theta+90°)$ in orthogonal channel PSD2.

Supposed that the amplitude of measured signal is V_s . The phase channel output I is as follows:

$$I = V_s \cos\theta \tag{1}$$

And the orthogonal channel output Q is described as the following expression:

$$Q = V_s \sin\theta \tag{2}$$

The amplitude V_s and the phase θ of the measured signal can be calculated by these two outputs. And the expression is as follows:

$$V_s = \sqrt{I^2 + Q^2} \tag{3}$$

$$\theta = \arctan(Q / I) \tag{4}$$

III. SIMULATION OF ANALOG ORTHOGONAL LIA

The LIA based weak signal detection system simulating model is constructed using MATLAB/SIMULINK software. As to this simulation model, the procedure of it is as follows. Firstly, the Gaussian Noise Generator is used to generate white noise, and the Signal Generator is used to simulate 50Hz industrial frequency noise interference. Then band-pass filter filters the added signal with the over-low and over-high frequency to achieve primary signal processing. After that, added signal multiplied reference signal in analog multiplier in PSD. In addition, low-pass filter filters AC (alternating current) component and extracts DC (direct current)

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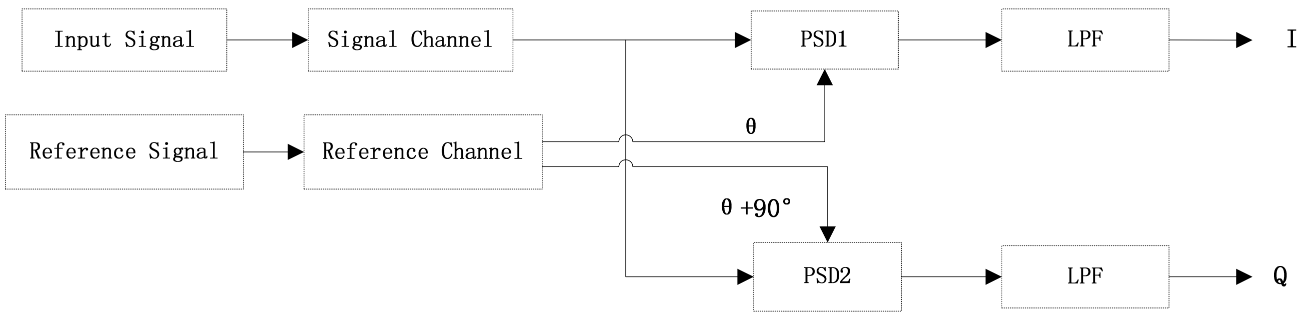

Fig.1 Schematic diagram of orthogonal vector LIA

component. Subsequently, this model uses some mathematical relation (to calculate the output dc component) to acquire useful value. Consequently, only the amplitude of input signal will be displayed as the value of display module. In another word, the data can be acquired easily.

The SNR can be calculated by MATLAB, and the definition is as follows:

$$power = \frac{x_1^2 + x_2^2 + \cdots + x_n^2}{n} \quad (5)$$

$$SNR = 10\lg(\frac{signalpower}{noisepower})(dB) \quad (6)$$

Where, n is sampling number, and x_n is sampling value of sampling point.

Two experiments have been applied to test this model.

A. Input Signal is Invariance

In this experiment, the variance of the white noise is from 1 to 100, and the amplitude of the measured signal is 1. Data are shown in Tab. I.

This table shows that the system works well even when the SNR is -23.

B. Power of Noise is Invariance

In this experiment, the value of the white noise is 1, and the value of the amplitude of measured signal is changeable. Data are shown in Tab. II, and it shows that the amplitudes of output are in proportion. From Tab. II, the error of output is still small compared with input even the SNR is -33.

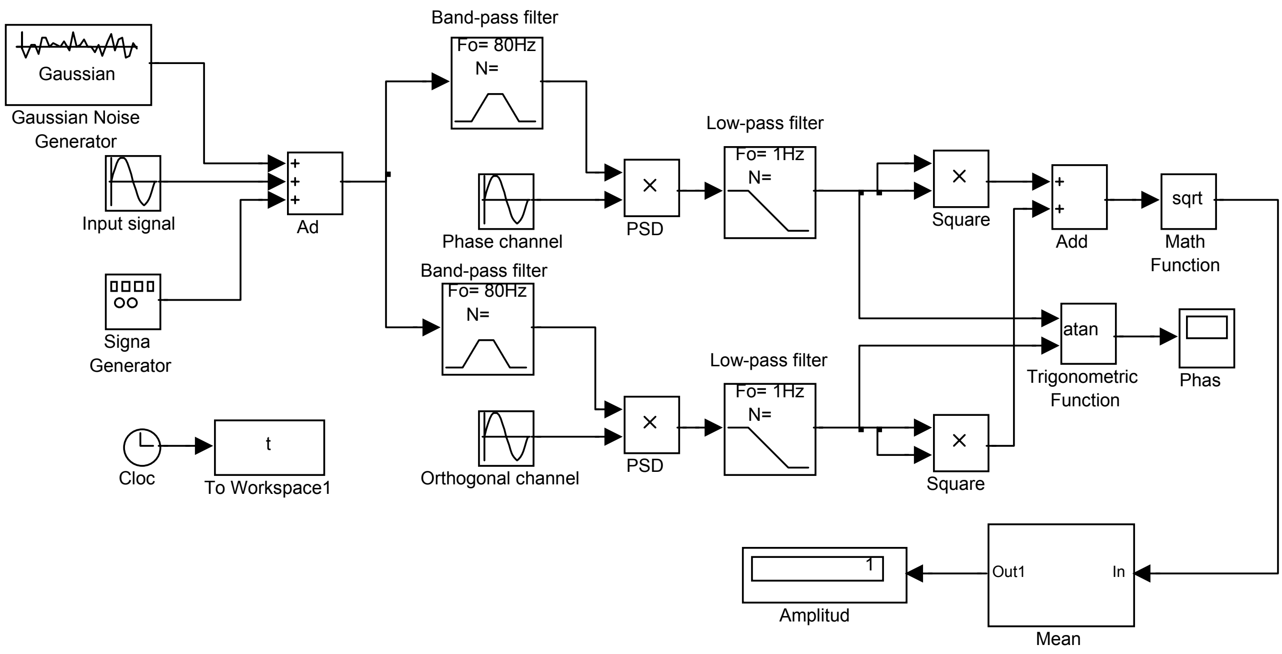

Fig.2 Simulation of orthogonal vector LIA

TABLE I.
THE VALUE OF OUTPUT WITH DIFFERENT NOSISE

SNR	-13.02	-16.03	-17.79	-19.04	-20.01	-20.8	-21.47	-22.05	-22.57	-23.02
Noise power	10	20	30	40	50	60	70	80	90	100
Output	0.9969	0.9978	0.9988	1	1.001	1.002	1.004	1.005	1.006	1.008

TABLE II.
THE VALUE OF OUTPUT WITH DIFFERENT INPUT

SNR	-6.121	-7.46	-9.04	-10.98	-13.48	-17	-23.02	-29.04	-30.98	-33.48
Input	0.7	0.6	0.5	0.4	0.3	0.2	0.1	0.05	0.04	0.03
Output	0.6976	0.598	0.4983	0.3987	0.2991	0.1997	0.1008	0.05265	0.0437	0.03548

IV. CIRCUITS DESIGN WITH TINA

A. *Design of Signal Channel*

In order to acquire the input signal, added weak signal and white noise through an adder circuit. In this circuit, an OPA227 and two resistors are used to achieve the composite signal. And the function of BPF is to filter lower frequency and higher frequency signal makes the frequency of output signal more close to the original signal's. In this channel, BPF center frequency is 80Hz, and it is designed by *TI FilterPro. Software.* The circuit of BPF is shown in Fig. 3.

B. *Design of Reference Channel*

In order to ensure the precision of the output of the reference signal, the sine wave signal is essential in the real detection [7]. The reference signal is sine wave which has the same frequency as the to-be-detected signal. At first, the reference signal shifts phase in phase-shift circuit, and then gets into PSD to drive multiplier. In this circuit, the range of phase shifter is from 0° to 180° adjustable, just control the sliding rheostat can change it. And the circuit is shown in Fig. 4.

C. *The Design of Phase Sensitive Detection*

The core of PSD is AD630 which is switching multiplier. The AD630 is a high precision balanced modulator. In this circuit, the sum-frequency signal and difference-frequency signal are acquired after measured signal and reference signal multiplied in PSD. The circuit is shown in Fig. 5.

D. *Design of Low-Pass Filter*

A low-pass filter is used to extract the DC component which is linear related to the amplitude of the measured low-level signal. Cut-off frequency of this filter is 1Hz. And the circuit is shown in Fig. 6.

In order to compare the results with the before MATLAB/SIMULINK simulition model, this paper carried out the other two experiments with TINA software simulation to verify the performance of this system.

1) *Input Signal is Invariance*

In this experiment, the white noise magnification is from 1 to 2.6. And the amplitude of the measured signal is 0.05V. Data are shown in Tab. III.

This table shows that the system works well even when the SNR is -19.

2) *Power of Noise is Invariance*

In this experiment, the white noise value is 0.04, and the value for the amplitude of measured signal is changeable. Data are shown in Tab. IV, and the plot is shown in Fig. 7. Through plotting these data by using MATLAB, the result shows that the relationship between input signal and output signal is linear. The relationship is shown in Fig. 8.

A polynomial which is calculated through curve fitting analysis is as follows:

$$f(x) = 0.0788x^2 + 3.0136x + 0.0038 \quad (8)$$

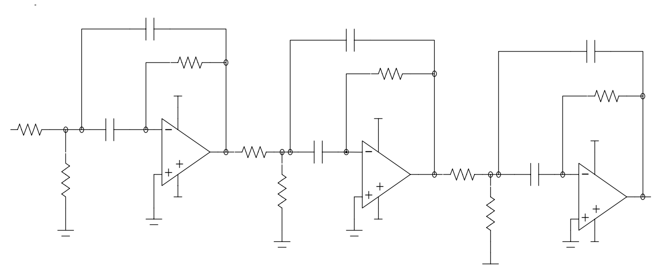

Fig. 3 Band-pass filter

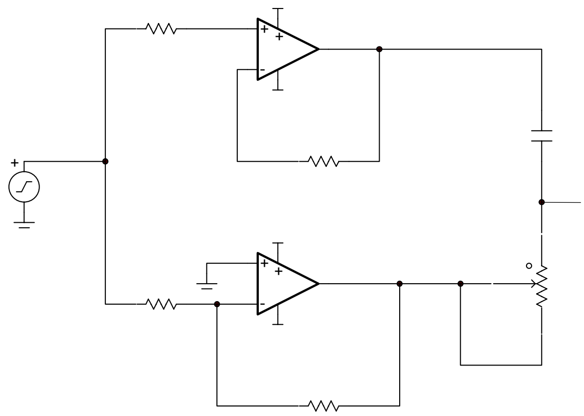

Fig. 4 Circuit of reference channel

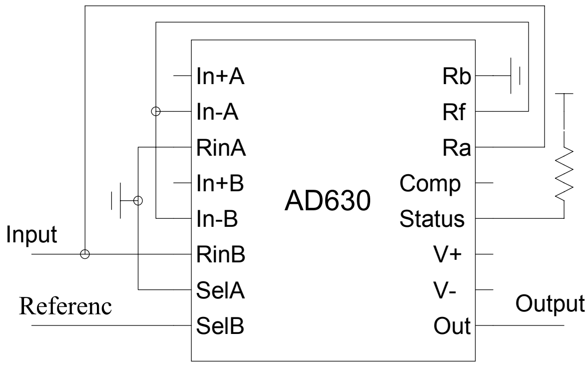

Fig. 5 Phase sensitive detection circuit

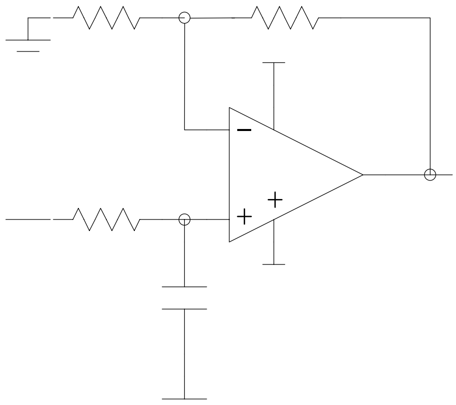

Fig. 6 Low-pass filter

TABLE III
THE VALUE OF OUTPUT IN DIFFERENT SNR

SNR	-15.856	-16.53	-17.11	-17.617	-18.074	-18.488	-18.87	-19.214
Noise power	0.048	0.056	0.064	0.072	0.08	0.088	0.096	0.104
Output(v)	0.05985	0.0596	0.0594	0.05922	0.059	0.05882	0.0586	0.05838

TABLE IV.
THE VALUE OF OUTPUT IN DIFFERENT INPUT

SNR	-15.0641	-15.979	-17	-18.16	-19.501	-21.085	-23.023	-25.52	-29.044
Input(v)	0.05	0.045	0.04	0.035	0.03	0.025	0.02	0.015	0.01
Output(v)	0.1547	0.1395	0.1245	0.1093	0.0942	0.0792	0.0641	0.049	0.0339

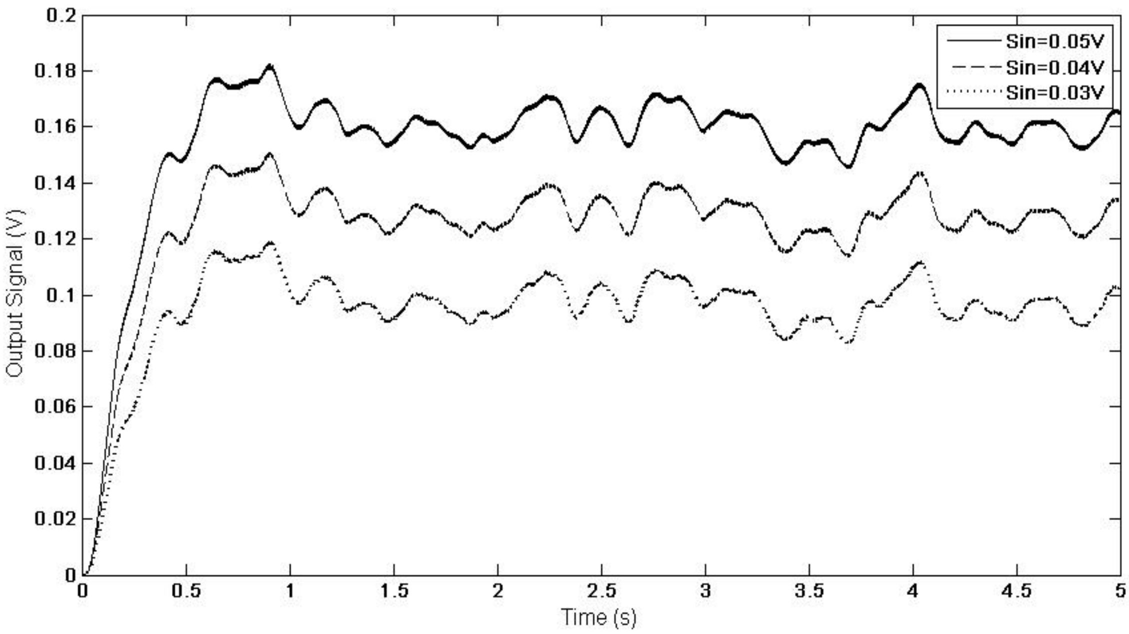

Fig. 7 Amplitude of output signal in different input

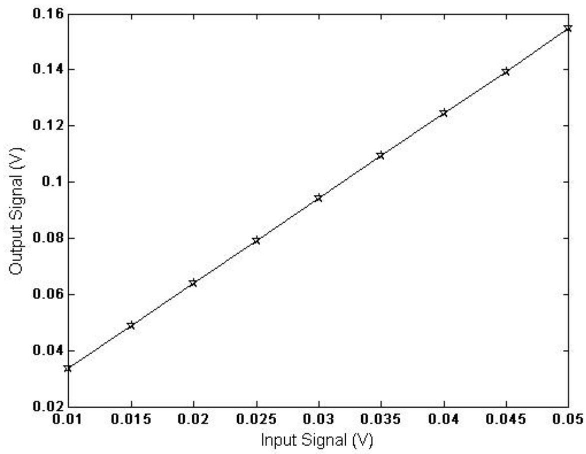

Fig. 8 Relationship between input and output

V. CONCLUSION AND PROSPECT

In this paper, four experiments proved that the circuit of weak signal detection based on the principle of orthogonal vector lock-in amplifier works well. The relationship between input signal and output signal is linear, so it is easy to make a calibration in device of weak signal detection. The simulation results indicate that the lock-in amplifier is an effective weak signal detection system and this is useful for the further study. At present, this system runs steadily in the simulation environment. In the future, the hardware circuit will be set up according to the system simulation. The system can be applied to linear variable differential transformer micrometer, de-noising of earphone, medical stethoscope, and so forth.

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