Design of the Weak Signal Detection Device Based on Multiplier Technology

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Abstract—In this paper, we present an effective weak-signal detection device to detect the amplitude of a weak signal in additive non-Gaussian noise of unknown level. Instead of using conventional phase lock amplifying and sampling integral, we apply a mixer based on multiplier technology and multilevel filtering technology for weak signals detecting. The whole device consists of a reverse adder, pure resistance voltage-divided network, a mixer based on multiplier technology, an amplifier section, a group of single-pole switches, a narrow band filter and a single-chip microcomputer-based display system. And the experimental waveforms and measurement results all show that the device is feasible, whose errors are pretty small in the allowable range.

I. INTRODUCTION

In recent years, the technology of weak signal detection is used in many fields, for instance, light, electric, magnet, sound, heat, biology, mechanics, geology, environment protection, medical science, laser, materials and so on [1]. So studying the new effective method and the device of weak signal detection is meaningful in the signal detection fields. There are a lot of conventional methods for the weak signal detection under the scenario of additive non-Gaussian noise of unknown level. For example narrow band filtering, synchronous cumulating, correlation detection, sample integral and so on. Each of them has its advantages and disadvantages. And new creative methods are also meaningful.

In the previous research, [2] pointed out a stability problem of level estimates from a finite, process record. They found that the time-bandwidth product for a stationary process represents a realistic upper bound on the number of independent samples from a process record. They also suggested that it is more reasonable to merely sample at the Nyquist rate than it is to perform a complicated projection transformation on the data to obtain independent reference samples. [3] suggested the use of a projection technique [4] for estimating the unknown noise level. By using this estimate, a detector can be constructed to achieve a performance as close as desired to that of a detector operating in a noise environment of known level.

Later, [5] derived an adaptive threshold receiver maintaining a specified false-alarm probability independent of changes in underlying Gaussian noise level. The adaptive threshold corresponds to the maximum likelihood estimates of the noise level. [6] used the concept of invariance in hypothesis testing on the problem of detecting signals of known form in Gaussian noise of unknown level. The derived detector was an optimum filter normalized by a maximum likelihood estimate of the noise level.

And [7] described the application of a phase-lock loop to provide power amplification of microwave FM communication signals. The device was intended to serve as the transmitting amplifier for microwave radio-relay communication linked for multiplex telephone message service and television. An experimental amplifier was described, together with the test data applicable to such service. The paper was largely theoretical, however, presenting an analysis of the relationships of the internal parameters of the phase-lock loop to the system performance expected.

In this paper, we focus on the design of the analog circuit of weak signal detection based on multiplier technology to test for the amplitude and frequency of a weak signal in additive non-Gaussian noise of unknown level. Without loss of generality, the whole device consists of a reverse adder, pure resistance voltage-divided network, a mixer based on multiplier technology, an amplifier section, a group of single-pole switches, a narrow band filter and a single-chip microcomputer-based display system. And a mixer based on multiplier technology is the most important and novel part in our paper. In the following, we begin with a description of the principle of the weak signal detection device based on the multiplier technology, followed by the introduce of the hardware design of the device, along with the experiment results and the analyzing remarks, and end with our conclusion.

II. THE PRINCIPLE OF WEAK SIGNAL DETECTION BASED ON MULTIPLIER TECHNOLOGY

In this section, we introduce the the principle of the weak signal detection device based on the multiplier technology. The multiplier technology, in fact, realizes signal modulation. Assume that the weak signal with the amplitude \(A_s\) of and the frequency of \(\omega_s\) is a sine wave as the following expression:

\[
V_s(t) = A_s \cos \omega_s t
\]

And the reference signal with the amplitude \(A_r\) of and the frequency of \(\omega_r\) is a sine wave as the following expression:

\[
V_r(t) = A_r \cos \omega_r t
\]

The output of the multiplier multiplying the above two signals is expressed as follows:

\[
V_m(t) = V_s(t) \times V_r(t) = A_s A_r \cos \omega_s t \cos \omega_r t
\]
Fig. 1. Components of the weak-signal detection device

And applying the property of the translation of the product and the sum, we have

\[ V_m(t) = \frac{A_s A_r}{2} \left[ \cos(\omega_s + \omega_r)t + \cos(\omega_s - \omega_r)t \right] \] (4)

In this way, we have divided the two different signals by dividing their frequencies, and then it’s easy to separate the two signals by filtering.

The above principle of the weak signal detection device based on the multiplier technology is the most important part of our device designment. And the whole device consists of a reverse adder, pure resistance voltage-divided network, a mixer based on multiplier technology, an amplifier section, a group of single-pole switches, a narrow band filter and a single-chip microcomputer-based display system, which is illustrated distinctly in figure 1. According to the components of figure 1, we design each part of the weak signal detection device and shows their circuits in the following part in detail.

III. THE DESIGN OF HARDWARE SYSTEM FOR WEAK SIGNAL DETECTION

In this section, we introduce our hardware circuit in detail. The whole device consists of a reverse adder, pure resistance voltage-divided network, a mixer based on multiplier technology, an amplifier section, a group of single-pole switches, a narrow band filter and a single-chip microcomputer-based display system.

Before the main components of the weak signal detection device, there is preliminary gain amplifier circuit to guarantee the input resistance greater than \( R_i \geq 1 \Omega \). We use the chip OPA642 whose gain is over 30 times to generate the phase-same arithmetic circuit which has an infinite value of the input resistance in the ideal state. And the preliminary gain amplifier circuit is shown as figure 2. In the following section, we introduce the reverse adder circuit and the mixer based on multiplier technology in detail, which are the most important parts in our design of the weak signal detection device.

A. Reverse Adder Circuit

We use chip OPA842 to realize a simple reverse adder circuit, as is shown in figure 3, which functions to add the noise signal and the weak sine signal. The OPA842 provides a level of speed and dynamic range previously unattainable in a monolithic op amp. Using unity-gain stable, voltage-feedback architecture with two internal gain stages, the OPA842 achieves exceptionally low harmonic distortion over a wide frequency range. The classic differential input provides all the familiar benefits of precision op amps, such as bias current cancellation and very low inverting current noise compared with wideband current differential gain/phase performance, low-voltage noise, and high output current drive make the OPA842 ideal for most high dynamic range applications.

B. Mixer Based on Multiplier Technology

We use a kind of multiplier chip AD835 to realize the mixer circuit, which is shown in figure 4. The AD835 is a complete four-quadrant voltage output analog multiplier fabricated on an advanced dielectrically isolated complementary bipolar process. It generates the linear product of its X and Y voltage.
inputs, with a C3 dB output bandwidth of 250 MHz. Full-scale rise or fall times are 2.5 ns and the settling time to 0.1% under the same conditions is typically 20 ns. Its differential multiplication inputs (X, Y) and its summing input (Z) are at high impedance. The low impedance output voltage (W) can provide up to 2.5 V and drive loads as low as 25 Ω. Normal operation is from 5 V supplies. Though providing state-of-the-art speed, the AD835 is simple to use and versatile. For example, as well as permitting the addition of a signal at the output, the Z input provides the means to operate the AD835 with voltage gains up to about 10 times. In this capacity, the very low product noise of this multiplier makes it much more useful than earlier products.

Just as figure 1 shows that the DDS which generates a sine signal of frequency of 9kHz and the primary mixed signal from the reverse adder through the pure resistance voltage-divided network and the group of single-pole switches are as two inputs into the mixer. Distinctly, as is shown in (3) and (4), we calculate that the weak signal of frequency of 1kHz has been transformed to a sine signal of frequency of 10kHz after adding the DDS signal of frequency of 9kHz.

Later, we design a mixed-signal amplifying circuit to amplify the mixed signal. The amplifying chip OP27 is used to form the simple phase-same rate arithmetic circuit. Since the mixed-signal amplifying circuit is similar with the preliminary gain amplifier circuit shown as figure 2, it is not shown in our paper. The OP27 precision operational amplifier combines the low offset and drift of the OP07 with both high speed and low noise. Offsets down to 25 uV and drift of 0.6 uV per C maximum make the OP27 ideal for precision instrumentation applications. Exceptionally low noise, at 10 Hz, a low 1/f noise corner frequency of 2.7 Hz, and high gain, allow accurate high-gain amplification of low-level signals.

And next, a multilevel filtering circuit which has six levels filtering is designed by us to get the useful signal and filter the noise signal, and the uni-level filtering circuit is simple to design. The other-level filtering circuits similar with the first level just have different values for resistances and capacitances.

At last, we use MSP430F2619 single-chip microcomputer-based display system to sampling and calculating to display the values of amplitude of the weak signal. The architecture of MSP430F2619, combined with five low-power modes is optimized to achieve extended battery life in portable measurement applications. The device features a powerful 16-bit RISC CPU, 16-bit registers, and constant generators that contribute to maximum code efficiency. The calibrated digitally controlled oscillator (DCO) allows wake-up from low-power modes to active mode in less than 1 s. The MSP430F2619 is the micro-controller configuration with two built-in 16-bit timers, a fast 12-bit A/D converter, a comparator, dual 12-bit D/A converters, four universal serial communication interface (USCI) modules, DMA, and up to 64 I/O pins.

And the output values of the display system depends on the true rms conversion circuit based on chip AD637 which is shown in figure 5. We get the effective value to compare with the primary data to estimate the performance of each circuit part. The AD637 is a complete, high accuracy, monolithic rms-to-dc converter that computes the true rms value of any complex waveform. It offers performance that is unprecedented in integrated circuit rms-to-dc converters and comparable to discrete and modular techniques in accuracy, bandwidth, and dynamic range. A crest factor compensation scheme in the AD637 permits measurements of signals with crest factors of up to 10 with less than 1% additional error. The wide band-width of the AD637 permits the measurement of signals up to 600 kHz with inputs of 200 mV rms and up to 8 MHz when the input levels are above 1 V rms.
IV. THE EXPERIMENT RESULTS

In this section, simulation results are presented to demonstrate the reasonability and feasibility of the design of our weak-signal detection device. In the above section, we present an effective weak-signal detection device to test for the amplitude of a weak signal in additive non-Gaussian noise of unknown level. We apply a mixer based on multiplier technology and multilevel filtering technology for weak signals detecting. The whole device consists of a reverse adder, pure resistance voltage-divided network, a mixer based on multiplier technology, an amplifier section, a group of single-pole switches, a narrow band filter and a single-chip microcomputer-based display system. And the experimental waveforms and measurement results in the following part all show that the device is feasible, whose errors are pretty small.

Firstly, we use Multisim Software, a schematic capture and simulation application, to assist us in carrying out the major steps in the circuit design and simulating the performance of our device. As is shown in figure.6, we get the spectral characteristic curve of the device for testing the performance of our device system. From figure.6, we find that our device system is a narrow-band system with a central frequency of 1KHz, which means that we can get the weak signal of frequency of 1KHz from the scenario of additive non-Gaussian noise of unknown level. From this, we can deduct that our system is effective to realize its function.

We get figure.7 through Multisim Software simulation, in which the long sine function curve is the weak signal we want and the broad and rambling curves are the additive non-Gaussian noise of unknown level. As the figure.7 shows, the weak signal we want in the scenario of additive non-Gaussian noise of unknown level can be separated distinctly from the additive non-Gaussian noise of unknown level. Comparing with the initial input signal, we find that the amplitude of the filtering weak signal we get is almost the same as the initial input signal.

Table.1 is the values of the amplitudes of the weak signals of different amplitudes displayed on the MSP430F2619 single-chip microcomputer-based display system recorded by us according to many tests for the whole weak signal detection device. In Table.1, I.Pp.mV means the initial input peak-to-peak values of the weak signals and its unit is mV. O.A.mV means the output effective values of the amplitudes of the weak signals and its unit is mV, too. The rows of Error display the error probability of the performance of the weak signal detection device. And the values in the table are not generally losing, since we test the whole device system enough times and get a number of similar results. So the values in the table are representative.

As is shown in the table, the output values of the amplitudes of the weak signals of different amplitudes are almost the same with the initial input values of the amplitudes of the weak signals of different amplitudes. For example, when the initial input peak-to-peak value of the weak signal is 20mV, the output effective value of the amplitude of the weak signal is 10mV, which means there is almost no error in the detection. And when the initial input peak-to-peak value of the weak signal is 40mV, the output effective value of the amplitude of the weak signal is 19mV, which means its detecting error is only 5% in the allowable range of error. As the input signal increases, the detecting errors is decreasing, which is pretty reasonable. And when the initial input peak-to-peak value of the weak signal is 2000mV, the output effective value of the amplitude of the weak signal is 1997mV, which means its detecting error is only 0.3% in the allowable range of error.

In summery, the experimental waveforms and measurement results all show that the method is feasible, whose errors are really small in the allowable range, which is probably of great significance and appliance for the next research on the weak-signal detection under the scenario of additive non-Gaussian noise of unknown level.
V. Conclusion

In our paper, we present an effective weak-signal detection device to test for the amplitude and frequency of a weak signal in additive non-Gaussian noise of unknown level. Since the conventional weak-signal detection technologies are filtering, phase lock amplifying, and sampling integral, we present a new method which applies multiplier technology to generate a mixer for weak signals detecting. The whole device consists of a reverse adder, pure resistance voltage-divided network, a mixer based on multiplier technology, an amplifier section, a group of single-pole switches, a narrow band filter and a single-chip microcomputer-based display system. And the experimental waveforms and measurement results all show that the method is feasible, whose errors are in the allowable range, which is probably of great significance and appliance for the next research on the weak-signal detection under the scenario of additive non-Gaussian noise of unknown level.

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<th>TABLE I</th>
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<td>Greedy Algorithm</td>
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References


