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An Arc Tangent Function Demodulation Method of Fiber-Optic Fabry-Perot High-Temperature Pressure Sensor

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Abstract: A new demodulation algorithm of the fiber-optic Fabry-Perot cavity length based on the phase generated carrier (PGC) is proposed in this paper, which can be applied in the high-temperature pressure sensor. This new algorithm based on arc tangent function outputs two orthogonal signals by utilizing an optical system, which is designed based on the field-programmable gate array (FPGA) to overcome the range limit of the original PGC arc tangent function demodulation algorithm. The simulation and analysis are also carried on. According to the analysis of demodulation speed and precision, the simulation of different numbers of sampling points, and measurement results of the pressure sensor, the arc tangent function demodulation method has good demodulation results: 1 MHz processing speed of single data and less than 1% error showing practical feasibility in the fiber-optic Fabry-Perot cavity length demodulation of the Fabry-Perot high-temperature pressure sensor.

Keywords: Arc tangent; Fabry-Perot; demodulation; pressure sensor

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1. Introduction

The traditional pressure sensor can't be well applied in the field of high-temperature pressure measurement. With the rapid development of engineering and technology, the accurate measurement of pressure in the harsh environment is increasingly required [1]. In this case, the fiber-optic Fabry-Perot pressure sensor has been widely researched due to its excellent advantages, such as the small size, immunity to electromagnetic interference, wide range of dynamic measurement, and high resolution, which have been applied in high-temperature environments, such as the high-speed missile surface and combustion chamber of space engine [2].

In the fiber-optic Fabry-Perot sensor measurement system, Fabry-Perot cavity length demodulation is of great importance. The popular demodulation methods include intensity demodulation and phase demodulation [3–6]. The

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former method has merits of simple structure, fast speed, ease to implement, small size, and low cost. However, the demodulation accuracy is generally low. The relevant proposed compensation methods all have influence on the light source to some extent, which also limit the measurement precision. The phase demodulation method has the advantages of high accuracy and good stability. However, most of the current phase demodulation systems are composed of large and expensive optical interferometers, which are difficult to be used in the practical engineering. In order to realize the application of the fiber-optic Fabry-Perot high-temperature pressure sensor in practical engineering, developing a high-precision, fast-rate, good-stability, and small-volume demodulation system is largely imperative [7–10].

The phase demodulation methods mainly include the fringe counting method, Fourier-transform method, and correlation method. The fringe counting method is mostly based on the peak-peak tracing method, thus the demodulation accuracy is affected by the accuracy of the peak wavelength, leading to low accuracy. The principle of the Fourier-transform method is complex. The correlation demodulation system is expensive. With the widespread use of digital techniques in instrumentation and communication systems, full digital demodulation has become the current trend of fiber-optic Fabry-Perot sensor demodulation, which has the advantages of high speed, high precision, and good stability. However, the traditional full digital demodulation method still combines with large optical instruments [11–14]. This paper proposes a new demodulation algorithm based on the phase generated carrier (PGC) arc tangent function and the analysis of several mature demodulation methods. The MATLAB simulation is carried out, the new algorithm is simulated using field-programmable gate array (FPGA) hardware, and the results are analyzed. As the results shown, the new algorithm expands the range of the original algorithm, verifying the feasibility of the arc tangent function demodulation method in the fiber-optic Fabry-Perot high-temperature pressure sensor demodulation.

2. Demodulation mechanism of the PGC arc tangent function method

The mechanism of the PGC arc tangent function method is to modulate the initial signal with the high-frequency and large-amplitude phase modulation signal [15–19]. The modulated optical signal is transmitted to the sensor, after which the phase variation of the optical signal is caused by the measured parameters. Then the signal propagates into the circulator, and the optical signal is converted into the electrical signal in the photodetector, outputting two signals, which are respectively mixed with the modulation signal and the double frequency modulation signal. Then the two modulation signals pass through the low-pass filter, and two quadrature signals are received. The optical circuit of modulation and demodulation system is shown in Fig. 1.

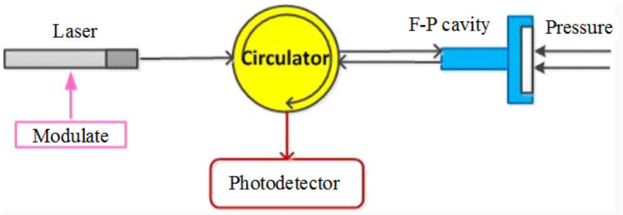

Fig. 1 PGC modulation and optical circuit schematic.

The light intensity signal is calculated as

$$I = \varphi A t + \mathrm{B}\cos\left[C\cos(\omega_0 t) + (\quad)\right] \tag{1}$$

where A and B are constants which are related to the power of the input light source and the response of the detector; $C\cos(\omega_0 t)$ is the carrier signal; $\varphi(t)$ is the signal to be measured, and this signal includes the low-frequency signal caused by the environmental drift.

Equation (1) is expanded into the first kind of Bessel function as

$$I = \mathrm{A} + \mathrm{B}\left\{\left[J_0(C) + 2\sum_{k=1}^{\infty}(-1)^k J_{2k}(C)\cos 2k\omega_0 t\right]\times\cos\varphi(t) - \left[2\sum_{k=0}^{\infty}(-1)^k J_{2k+1}(C)\cos(2k+1)\omega_0 t\right]\sin\varphi(t)\right\} \tag{2}$$

where $J_k(C)$ is the first kind of Bessel function of order k.

The signal I is mixed with the output signals $G\cos\omega_0 t$ and $H\cos 2\omega_0 t$, respectively. Then the high-frequency signal is filtered by a low-pass filter, and the two quadrature signals are received. The two signals are shown as follows:

$$-\mathrm{B}GJ_1(C)\sin\varphi(t) \tag{3}$$

$$-\mathrm{B}HJ_2(C)\cos\varphi(t). \tag{4}$$

And $(3)/(4)$ can be obtained as follows:

$$\frac{G\times J_1(C)}{H\times J_2(C)}\tan\varphi(t). \tag{5}$$

In general, for the operation simple, we can take $G = H$, and the coefficient of (5) will be $J_1(C)/J_2(C)$. Firstly, the coefficient of (5) is normalized. And then the arc tangent operation is carried out. Finally, using the high-frequency filter to filter out the low-frequency signal caused by the environment, the signal $\varphi(t)$ is received. The traditional PGC arc tangent demodulation method is shown in Fig. 2.

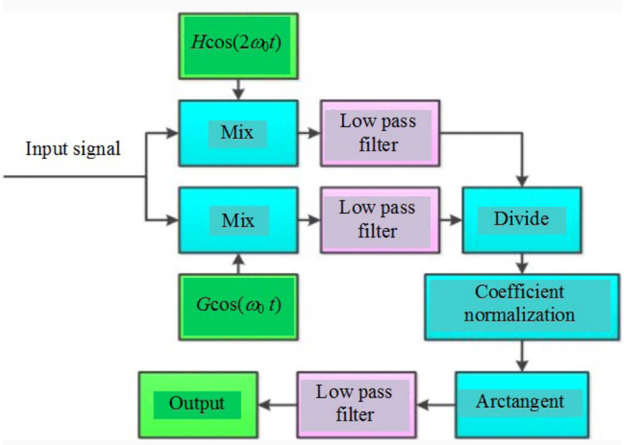

Fig. 2 Schematic of the PGC arc tangent demodulation method.

3. Algorithm simulation and analysis

The maximum detectable signal amplitude of the PGC demodulation algorithm is affected by the amplitude C and the frequency of the modulated signal. If the signal amplitude is beyond or near this range, the demodulation result will be distorted. It is enough to be applied in the interference hydrophones which have a little range of phase change. However, it can't meet the use requirement of the fiber-optic Fabry-Perot pressure sensors which have a large range of phase variation.

The relationship between the cavity length and phase is described as

$$\Delta L = \frac{\Delta\varphi(t)\lambda}{2\pi} \tag{6}$$

where ΔL is the Fabry-Perot cavity length variation; $\Delta\varphi(t)$ is the phase variation; λ is the laser wavelength.

Using (6) to calculate the cavity length variation of the fiber-optic Fabry-Perot high-temperature pressure sensor developed by our laboratory, in the range of 0−5bar, the phase change range is $0-4.6\pi$. It is not enough to use the traditional arc tangent function method. Therefore, it is necessary to enlarge the range of the demodulation algorithm.

The output signal of the PGC demodulation algorithm is simulated by MATLAB. As shown in Fig. 3, $\varphi(t)=10\sin t$. As shown in Fig. 4, the phase jump will appear in the traditional algorithm of phase demodulation. At the jump position, the difference between the phase value of the latter point which is output by the phase demodulation and the original phase value is π. According to the result, a new algorithm which can compensate the phase is designed by using MATLAB. The result is shown in Fig. 5.

The first part of this algorithm is the setup of two thresholds: one is positive, and the other is negative. When the previous data are greater than the positive threshold and the latter data are less than the negative threshold, it is regarded as a jump point, and the FPGA will add all the following data to π. Conversely, if the previous data are less than the negative threshold and the latter data are greater than the positive threshold, the FPGA will subtract π from all the following data. Through the new arc tangent algorithm, the initial signal data are restored. Thus, the demodulation range of the arc tangent function method is expanded.

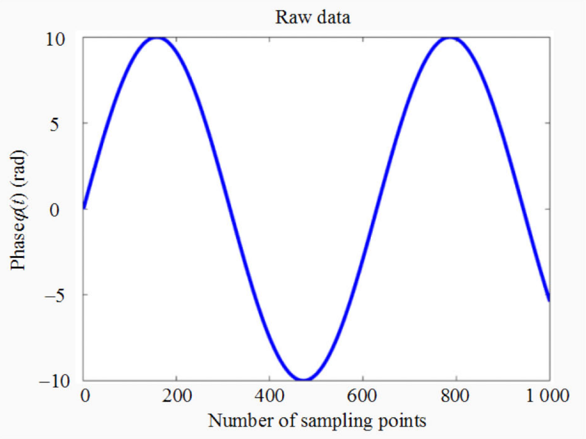

Fig. 3 Original signal $\Delta\varphi(t)$.

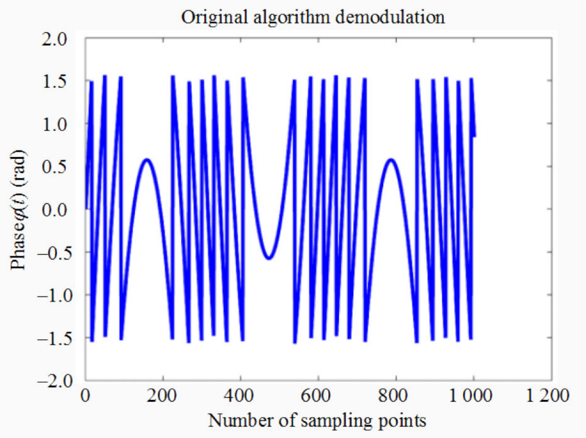

Fig. 4 Original algorithm demodulation signal.

It can be seen from Fig. 3 to Fig. 5 that the algorithm solves the shortcomings of the traditional arc tangent function demodulation method in theory. The requirement of the application of the fiber-optic Fabry-Perot high-temperature pressure sensor is satisfied. The phase change range can satisfy the change range of the fiber-optic Fabry-Perot cavity. Using this new algorithm, the demodulation of the fiber-optic Fabry-Perot sensor is easier to realize full digital demodulation, and it is easy to use the FPGA to achieve the method. At the same time, the new demodulation method will also use the optical system for the optical signals orthogonal processing. After the orthogonal processing, optical signals are converted into electrical signals by the photoelectric converter which can reduce the interference caused by the circuit.

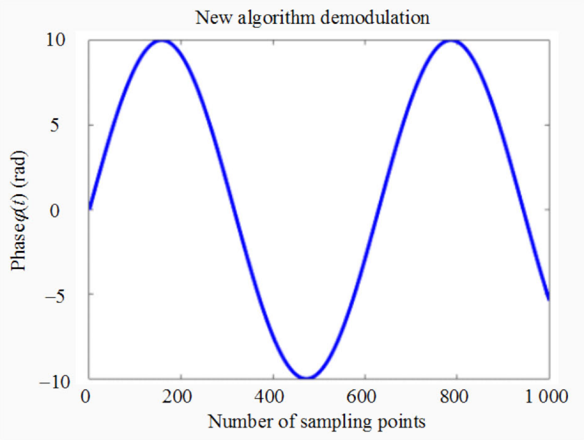

Fig. 5 New algorithm demodulated signal.

4. FPGA design and data simulation

This paper selects the Cyclone IV series EP4CE30F23C8N chip of Altera Company. Cyclone IV E has low power consumption, and it can achieve high functionality with very low cost. EP4CE30F23C8N chip which uses 1.2 V power supply, with 329 user I/O ports, the 28848 logic units, 594 KB embedded memory and the 4 general PLLs, which can satisfy the requirements of the hardware design.

The realization of the design process is shown in Fig. 6. Orthogonal signals 1 and 2 are generated by the MATLAB simulation of the two orthogonal signals. Using very-high-speed integrated circuit hardware description language (VHDL) to compile the FPGA module to control the IP core computing and data processing, the results are stored in the first input first output (FIFO) IP core. Finally, the serial port will output the data. The two data are simulated, and the initial signals of the two simulations are sine wave with an amplitude of 10 rad. The numbers of sampling points are 64 and 256, respectively. The simulation results are shown in Figs. 7 and 8.

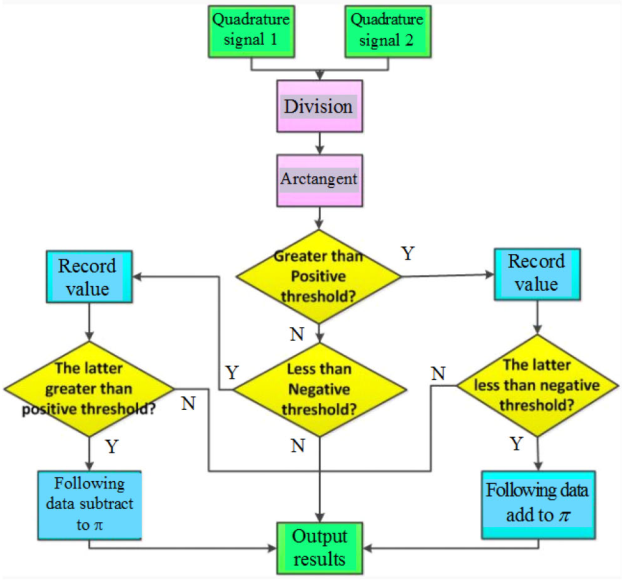

Fig. 6 Flow chart of new algorithm.

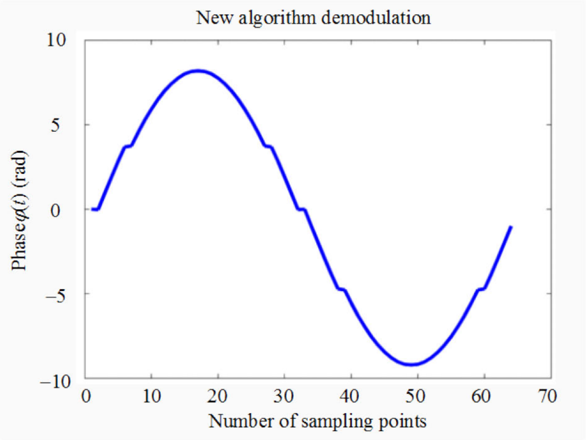

Fig. 7 FPGA simulation result of 64 sampling points.

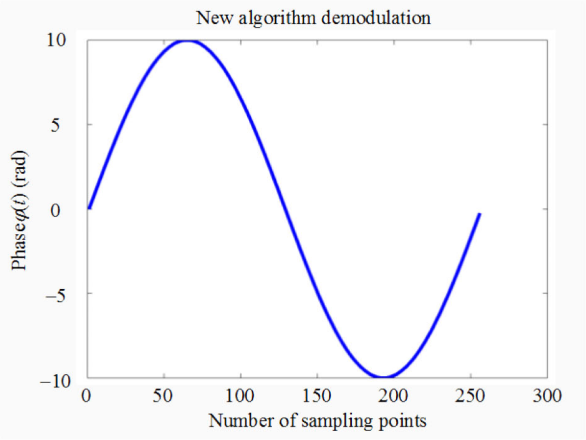

Fig. 8 FPGA simulation result of 256 sampling points.

It can be seen from Figs. 7 and 8 that when the signal amplitude is 10 rad, it is not enough to demodulate the signal which samples 64 points in each cycle. When the number of sampling points is increased to 256, the waveform of the signal is demodulated completely, and the error is less than 1%. Because the time of a single data demodulation is about 0.7 μs, the demodulation time of the full waveform is about 179 μs. Theoretically, if the sampling rate is equal to the above, when the signal frequency of 10 rad is below 5 kHz, the signal can be demodulated completely. Because the output phase signal of the fiber-optic Fabry-Perot high temperature pressure sensor is dominated by the low- frequency signal, the current pressure tests can be satisfied. Using the fiber-optic Fabry-Perot pressure sensor developed in our laboratory, each pressure changes from 0 bar to 1 bar, and the phase variation is approximately 0.92π. That means, in theory, if the pressure variation is less than 1 bar within 12.5 μs, the new demodulation algorithm can satisfy the test requirements.

5. Conclusions

By the MATLAB simulation, FPGA simulation, and results analysis, the feasibility of the new algorithm is verified preliminarily. The new algorithm overcomes the existing shortcomings of the traditional PGC demodulation algorithm, and it expands the range to satisfy the requirements of fiber-optic Fabry-Perot high-temperature pressure sensor demodulation. Compared with the general fiber-optic Fabry-Perot pressure sensor demodulation algorithm, the new arc tangent algorithm has the advantages of fast speed, simple principle, high accuracy, and low cost, so it is expected to become a new mainstream demodulation method, providing a new idea for the future of the arc tangent function demodulation algorithm in the fiber-optic Fabry-Perot pressure sensor in high temperature application.

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