All-digital demodulation system of interferometric fiber optic sensors using an improved PGC algorithm based on fundamental frequency mixing

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We present an all-digital demodulation system of interferometric fiber optic sensor based on an improved arctangent-differential-self-multiplying (arctan-DSM) algorithm. The total harmonic distortion (THD) and the light intensity disturbance (LID) are also suppressed, the same as those in the traditional arctan-DSM algorithm. Moreover, the lowest sampling frequency is also reduced by introducing anti-aliasing filter, so the occupation of the system memory is reduced. The simulations show that the improved algorithm can correctly demodulate cosine signal and chirp signal with lower sampling frequency.
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Interferometric fiber optic sensors are extremely sensitive sensors[1,2]. In order to demodulate the phase shift signal from the interferometric fiber optic sensors, several phase demodulation techniques have been proposed[3-5]. Due to the good linearity, the large dynamic range and the capability of real-time demodulation, the phase generated carrier (PGC) demodulation technique is widely used[6]. There are two kinds of PGC demodulation algorithms, which are the differential-and-cross-multiplying (DCM) algorithm and the arctangent (arctan) algorithm. In DCM demodulation algorithm, the light intensity disturbance (LID) becomes obvious when light intensity changes rapidly[7]. In arctan demodulation algorithm, the total harmonic distortion (THD) will be affected significantly when the modulation depth C deviates from 2.63 rad. To suppress LID and THD, arctangent-differential-self-multiplying (arctan-DSM) algorithm is proposed[8]. However, these algorithms increase the cost for their high sampling frequency.

With the advantages of flexibility, stability and facility to debug, the all-digital demodulation systems become more and more popular for interferometric fiber optic sensors. The lowest sampling frequency is particularly essential for the process of analog-to-digital conversion at the output of photodetector. An improved algorithm on the basis of tripling frequency mixing is presented[9], which eliminates the effect of the parasitic amplitude modulation, but increases the sampling frequency inevitably. An improved algorithm on the basis of the fundamental frequency mixing is also proposed[10], which improves the efficiency of the whole demodulation system and reduces the sampling frequency, but it is only suitable for small signals. These improved algorithms are implemented at the cost of losing some performance of the systems.

In this paper, we propose an all-digital demodulation system of interferometric fiber optic sensor with a PGC demodulation algorithm based on traditional arctan-DSM algorithm and fundamental frequency mixing. The algorithm inherits the advantages of high stability, low harmonic distortion and high efficiency from the arctan-DSM algorithm, and reduces the lowest sampling frequency of the system. Both cosine signal and chirp signal are correctly demodulated without THD or LID by using a lower sampling frequency in this system.

In the demodulation system, the output light intensity of interferometer is shown as

$$I = A + B\cos[C\cos\omega_0 t + \phi_s(t)] , \quad (1)$$

where A is proportional to the input optical power, which represents the direct current (DC) component, B is interference light intensity, which represents the intensity of alternating current (AC) component, A and B are constants, C is the modulation depth, ω_0 is the angular frequency of carrier, and $\varphi_s(t)$ is the sensor signal.

To recover the sensor signal from the interference signal without THD and LID, the arctan-DSM algorithm is proposed, which combines the improved DCM algorithm

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and the arctan algorithm. Firstly, the improved DCM operation is used to derive the coefficient $J_1(C)/J_2(C)$, where $J_1(C)$ and $J_2(C)$ are the first-order and the second-order Bessel functions, respectively. Then this coefficient can be associated with the arctan algorithm to cancel the coefficient. Finally, the arctangent operation is used to demodulate the sensor signal[8].

In the demodulation process, the interference light intensity B and the modulation depth C are eliminated, so the demodulation is not affected by LTI and THD.

Although the traditional arctan-DSM demodulation algorithm has many advantages, these algorithms increase the cost for their high sampling frequency. Therefore, we improve it based on fundamental frequency mixing.

At first, the pretreatment process, which includes photoelectric conversion, amplification, DC filtering and anti-aliasing filtering, is applied to the interference signal before PGC demodulation. The DC filter is used for filtering the DC component and retaining the AC component in order to implement the improved algorithm. Not all the frequency components of interference signal are essential for demodulation. In order to reduce the sample frequency, only the useful frequency components are preserved through the anti-aliasing filtering.

Then the improved PGC demodulation algorithm is applied. After the pretreatment process, the interference signal is divided. One divided signal is mixed with the carrier signal with frequency of ω_0, and the mixed signal is filtered out by lowpass filter (LPF). Another divided signal is directly filtered out by LPF. Thus a pair of quadrature signals is obtained as

$$E_1(t) = -BJ_1(C)\sin\phi_s(t) , \tag{2}$$

$$E_2(t) = BJ_0(C)\cos\phi_s(t) . \tag{3}$$

Making the differential-self-multiplication operation on the pair of quadrature signals, it can be produced that

$$E_3(t) = B^2 J_1^2(C)\cos\phi_s(t)\sin\phi_s(t)\cdot\phi_s'(t) , \tag{4}$$

$$E_4(t) = -B^2 J_0^2(C)\sin\phi_s(t)\cos\phi_s(t)\cdot\phi_s'(t) . \tag{5}$$

Then the sensor signal $\varphi_s(t)$ can be obtained by solving Eqs.(2)–(5).

Compared with the traditional arctan-DSM demodulation system, the fundamental frequency mixing and negative operation are introduced. The same as the arctan-DSM algorithm, the improved algorithm is still not affected by LTI and THD. However, the improved algorithm influences the lowest theoretical sampling frequency.

Introducing only the fundamental carrier to mix, the efficiency of the whole demodulation process can be improved[10], and the bandwidth of essential components of interference signal is around $\omega_0+\omega_d$, where ω_d is the width of side band and is no more than $\omega_0/2$[11].

An example of frequency spectrum of input signal is shown in Fig.1. After anti-aliasing filtering, only the frequency lower than $\omega_0+\omega_d$ is retained. Based on the Nyquist's sampling theorem, the sampling frequency F_s can be expressed as

$$F_s \geq 2(\omega_0+\omega_d) = 3\omega_0 . \tag{6}$$

So $3\omega_0$ is the lowest theoretical sampling frequency to demodulate the signal without distortion. Compared with the traditional demodulation system, the sampling frequency is significantly reduced. In practice, the sampling frequency should be larger than the lowest theoretical sampling frequency.

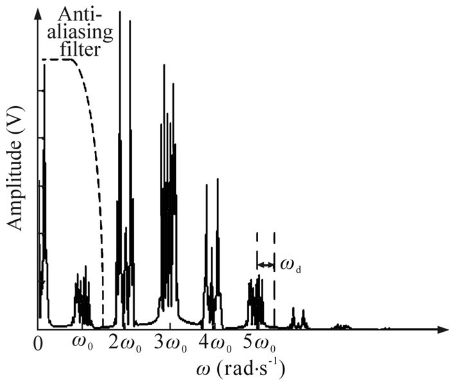
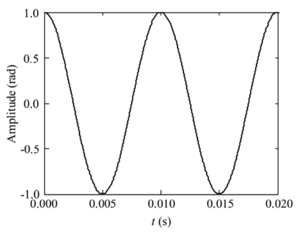
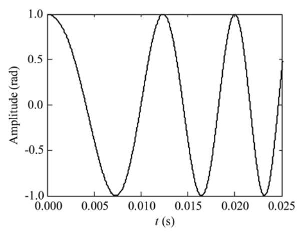


Fig.1 Frequency spectrum of the input signal with modulation depth of *C*=3.5 rad

Based on the Matlab simulation platform and the code composer studio (CCS) of digital signal processor (DSP), the above analysis results are verified. The carrier signal is assumed to be the sine wave whose frequency and amplitude are 10 kHz and 3.5 rad, respectively. There are two different sensor signals in this simulation. One is a cosine signal which can be expressed as $\varphi_s(t)=D\cdot\cos(2\pi f_s t)$, and the other is a chirp signal which can be expressed as $\varphi_s(t)=D\cdot\cos[2\pi(f_2 t+ f_1)t]$, which are shown in Fig.2. The sampling frequency is set to be 100 kHz in simulation.



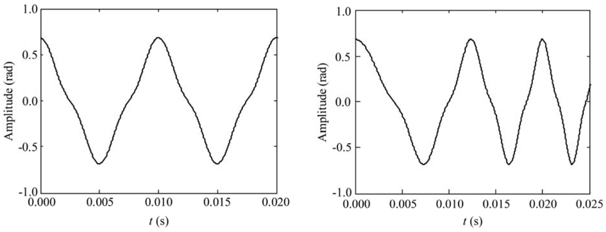
(a) Cosine signal with D=1 rad and f_s=100 Hz



(b) Chirp signal with D=1 rad, f_2=2 500 Hz and f_1=50 Hz

Fig.2 Two different sensor signals

The simulation results of arctan demodulation algorithm for the sensor signals in Fig.2 are shown in Fig.3. In Fig.3(a), the arctan demodulation of the cosine signal has THD seriously when the modulation depth is not 2.63 rad (C=3.5 rad). It can be seen from Fig.3(b) that the arctan demodulation of the chirp signal is also affected by the THD similarly. The results of the DCM demodulation algorithm for the sensor signals in Fig.2 are shown in Fig.4. In Fig.4(a) and (b), it can be seen that the demodulation results of two signals are affected by LID when the interference light intensity changes as B=2 V, 3 V and 5 V.



(a) (b)

Fig.3 (a) Demodulation cosine signal and (b) demodulation chirp signal of arctan demodulation algorithm with B=1 V, C=3.5 rad, f_0=10 kHz and F_s=100 kHz

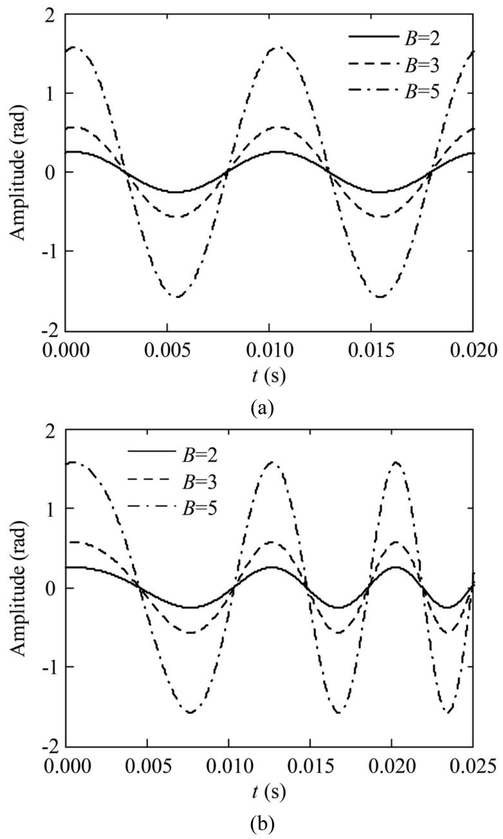
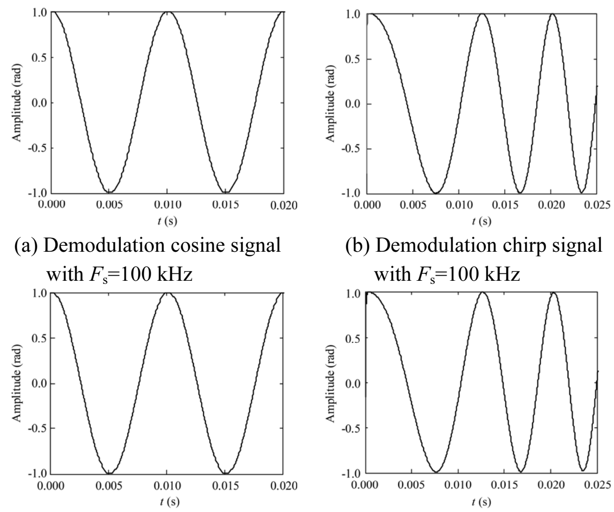


Fig.4 (a) Demodulation cosine signals and (b) demodulation chirp signals of DCM demodulation algorithm for B=2 V, 3 V and 5 V with C=3.5 rad, f_0=10 kHz and F_s=100 kHz

However, the improved arctan-DSM demodulation algorithm is not influenced by the modulation depth C and interference intensity B. The simulation results of the arctan-DSM demodulation algorithm for the sensor signals in Fig.2 are shown in Fig.5(a) and (b). Moreover, the sample frequency is reduced by introducing an anti-aliasing filter and using fundamental frequency mixing. So the sample frequency is reduced to 60 kHz, and the improved algorithm can still be demodulated correctly. The results of the improved arctan-DSM demodulation algorithm with F_s=60 kHz are shown in Fig.5(c) and (d).

A DSP development board (TMS320C5509a) is adapted to the experiment. According to the previous theoretical analyses, the sample frequency of F_s is set as 60 kHz. The sensor signal and the carrier signal are the same as those in Matlab simulation. Based on fundamental frequency mixing, the improved algorithm reduces the computation of DSP, so as to improve the efficiency of the whole digital demodulation system. In the experiment, the improved algorithm is implemented by the demodulation system. The results of the demodulation system for the cosine signal and the chirp signal in Fig.2 are shown in Figs.6 and 7, respectively. The demodulation system is adapted to fixed-point DSP, so it must be calibrated for data in the system. The signal amplitude is expressed by calibration of Q15. As shown in Figs.6 and 7, it can be proved that the improved demodulation system can demodulate the cosine signal and the chirp signal correctly.



(a) Demodulation cosine signal with F_s=100 kHz (b) Demodulation chirp signal with F_s=100 kHz

(c) Demodulation cosine signal with F_s=60 kHz (d) Demodulation chirp signal with F_s=60 kHz

Fig.5 The demodulation results of cosine signal and chirp signal using improved arctan-DSM demodulation algorithm with B=3 V, C=3.5 rad, f_0=10 kHz and F_s=100 kHz and 60 kHz

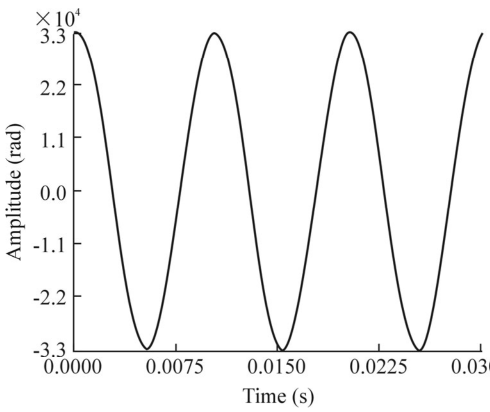


Fig.6 The demodulation cosine signal of the improved algorithm on CCS (B=3 V, C=3.5 rad, D=1 rad, f_0=10 kHz, f_s=100 Hz and F_s=60 kHz)

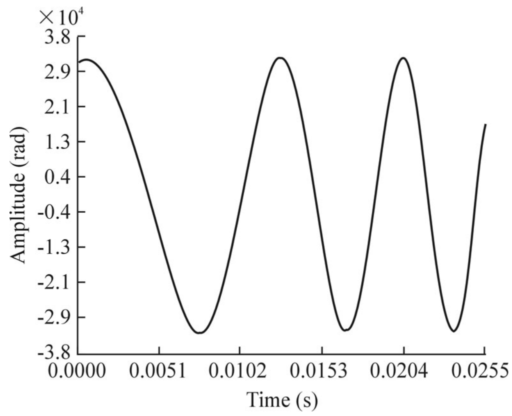


Fig.7 The demodulation chirp signal of the improved algorithm on CCS (*B*=3 V, *C*=3.5 rad, *D*=1 rad, f_0=10 kHz, f_2=2 500 Hz, f_1=50 Hz and F_s=60 kHz)

Any complex signal can be expressed as the combination of a series of cosine signals with different frequencies. So any complex signal can be demodulated by the improved demodulation system correctly with lower sampling frequency based on Fourier transform theory, so it can be convinced that the improved demodulation system can demodulate any signal.

In this paper, an all-digital demodulation system with an improved PGC algorithm based on fundamental frequency mixing is performed. The improved algorithm reduces the lowest sampling frequency and the cost of interferometric fiber optic sensor demodulation system. Moreover, the demodulation system can demodulate both cosine signal and chirp signal without THD and LID by using the improved algorithm. Furthermore, based on Fourier transform theory and the demodulation of the chirp signal, it can be inferred that any complex signal can be demodulated with the demodulation system. The results of simulation and experiment are in good agreement with the theoretical analysis. It has important significance for the design of interferometric fiber optic sensor demodulation system.

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