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Precise digital demodulation for fiber optic interferometer sensors

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Different methods are used in the interferometer sensors for target signal extraction. Digital technologies provide new opportunities for precise signal detection. We have developed the principle of signal demodulation using an additional harmonic phase modulation and digital signal processing. The principle allows implementation of processing algorithms using different ratios between modulation and discretization frequencies. The expressions allowing calculation of the phase difference using the inverse trigonometric functions were derived. The method was realized in LabVIEW programming environment and was demonstrated for various signal shapes.

Keywords: Fiber optic sensor; interferometer; polarization; phase modulation; digital signal processing.

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1. Introduction

Fiber-optic interferometers are widely used nowadays along with other devices that utilize the modulation of optic waves parameters by some physical value. This occurs due to the development of laser and fiber-optic technologies as measuring devices. The photodetector output of the interference system is

$$u(t) = U_0 + U_m \cos[\phi_S(t)], \tag{1}$$

where $\phi_S(t)$ is a target phase difference carrying information about the measured value, U_0 is a constant component, U_m is an interferometer signal amplitude. However, such a signal does not provide means to determine $\phi_S(t)$ uniquely. Moreover,

the constant component and the interferometer signal amplitude can fluctuate in time. Because of these factors determining of the target phase difference $\phi_S(t)$ becomes a complicated task.

The problem of phase demodulation can be solved by applying additional phase modulation and analog processing of the interferometer signal. Many of these methods use harmonic additional modulation. In this case the interference signal acquires the form

$$u(t) = U_0 + U_m \cos[\phi_S(t) + \phi_m sin(\omega_m t)].$$ (2)

For the signal given by Eq. (2) analog devices are able to determine the target phase difference by synchronous detecting, summation, differentiating, integrating, etc. A so-called pseudo heterodyne method is another well-known algorithm based on the additional phase modulation. There the signal formed at the photo receiver out-put becomes

$$u(t) = U_0 + U_m \cos[\phi_S(t) + \omega_m t].$$ (3)

To demodulate this signal traditional analog phase metric devices can be utilized.

Digital technologies provide new opportunities to demodulate interferometer signals.[1] Of course, digital methods are more effective when they are not just a digital implementation of the analog algorithms,[2] but utilize, for example, calculation of inverse trigonometric functions,[3] Hilbert transform[4] and even more complicated procedures,[5] that cannot be implemented using analog signal processing.

2. Demodulation Method

Here we present the results of implementation of previously described digital demodulation algorithm of the fiber interferometer signal using additional phase modulation.[6] The main concept of this method is that digital processing enables implementation of various mathematical procedures and there is no need to obtain the relatively simple signal like Eq. (3). So interferometer output signal used for processing can be of more complex shape but easier to be obtained in optical scheme.

This method enables implementation of demodulation with various parameters. The essential requirement for this approach is using of signal with shape described by Eq. (2). In this case, ϕ_S, U_0, U_m can vary. Oscillation of ϕ_S, bears useful information. Fluctuations of U_0, Um are hindering, but considered slow enough in comparison with the period of the modulating signal.

The basis of the demodulation method is calculating of a single value of the target phase ϕ_S, using three interference signal samples per every modulation period. These samples are taken under different values of the additional phase difference caused by the modulation applied. The necessity of using of three samples can be explained as follows. The function given by Eq. (2) describes the modulated interference signal. It includes three unknown parameters that are supposed to be constant while taking samples: target phase ϕ_S, U_0, and U_m. Let us denote these three

samples $\{u^{(0)}, u^{(1)}, u^{(2)}\}$, and values of the modulating phase signal $\{\phi^{(0)}, \phi^{(1)}, \phi^{(2)}\}$, respectively. Then, the system of equations with these unknown parameters can be written as

$$u^{(0)} = U_0 + U_m \cos{(\phi_S + \phi^{(0)})},$$
$$u^{(1)} = U_0 + U_m \cos{(\phi_S + \phi^{(1)})},$$
$$u^{(2)} = U_0 + U_m \cos{(\phi_S + \phi^{(2)})}. \tag{4}$$

Using trigonometric formulas and denoting $\cos[\phi^{(0)}] = C_0$, $\cos[\phi^{(1)}] = C_1$, $\cos[\phi^{(2)}] = C_2$ and $\sin[\phi^{(0)}] = S_0$, $\sin[\phi^{(1)}] = S_1$, $\sin[\phi^{(2)}] = S_2$, U_0 and U_m can be excluded. Hence, the formula for a tangent of the target phase is

$$\tan \phi_S = \frac{(u^{(0)} - u^{(1)})(C_1 - C_2) - (u^{(1)} - u^{(2)})(C_0 - C_1)}{(u^{(1)} - u^{(2)})(S_1 - S_0) - (u^{(0)} - u^{(1)})(S_2 - S_1)} = \frac{a}{b}, \tag{5}$$

where

$$a = (u^{(0)} - u^{(1)})(C_1 - C_2) - (u^{(1)} - u^{(2)})(C_0 - C_1),$$
$$b = (u^{(1)} - u^{(2)})(S_1 - S_0) - (u^{(0)} - u^{(1)})(S_2 - S_1). \tag{6}$$

In view of the formula for a tangent, the target phase ϕ_S in the range $[-\pi, \pi]$ can be found using the following equations:

$$\phi_S = \arctan\left[\frac{a}{b}\right], for \; b > 0;$$

$$\phi_S = \arctan\left[\frac{a}{b}\right] + \pi sign(a), for \; b < 0. \tag{7}$$

3. Implementation of the Demodulation Method

We have carried out a series of experiments to test the demodulation method, using an experimental model of a fiber-optic polarization sensor designed for electric field measurement.[7] It contained an additional polarization modulator that provided the sine modulation to recover the target signal $\phi_S(t)$. The shematic of our experimental setup is shown in Fig. 1. The output signal of this system can be described by Eq. (2), which allows application of the considered demodulation method.

The LabVIEW program controlled the hardware, displayed the results and wrote them to file. An additional modulation signal was formed using 16-bit arbitrary waveform generator NI PXI-5421. Signal parameters were chosen according to the demodulation method protocol.[6] The additional modulation frequency was 10 kHz.

The digitizer NI PXIe-5122 registered the interference signal from the photodetector output. The signal sampling frequency was set in accordance with the number of samples processed per every modulation period. Cases with samples per period N=3, 4 and 5 were considered.
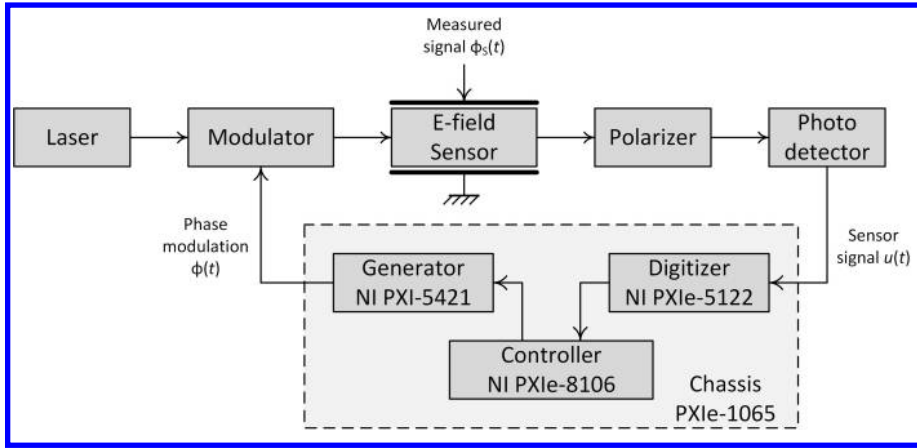
Fig. 1.   Experimental setup.

Samples of the additional modulation signal ϕ_n and of the interference signal u_n can be written as follows

$$\phi_n = \phi(t_n) = \delta\phi_m \sin\left[2\pi f_M(t_n + \Delta t)\right] = \delta\phi_m \sin\left[\left(\frac{2\pi n}{N}\right) + \Theta_0\right],$$

$$u_n = u(t_n) = U_0 + U_m \cos\left[\phi_S + \phi_n\right]$$

$$= U_0 + U_m \cos\left[\phi_S + \delta\phi_m \sin\left\{\left(\frac{2\pi n}{N}\right) + \Theta_0\right\}\right], \qquad (8)$$

where n is the sample number starting from the beginning of the first modulation period ($n = 0, 1, 2, \cdots$), t_n is the time of the n-th sample, Δt and $\Theta_0 = 2\pi f_M \Delta t$ are time delay and a corresponding phase shift of the first sample relatively to the beginning of the first modulation period. In our experiments the sampling sequence was synchronized with the modulating signal without delay ($\Delta t = 0$) regardless of the number of samples N chosen.

Figure 2 shows the acquisition points for different values of N marked on the experimental modulation and interference signals charts.

Acquisition points for the case of $N = 3$ are marked with squares. According to the method modulation phase values are

$$\phi_0 = \delta\phi_m \sin\left[\left(\frac{2\pi \cdot 0}{3}\right) + \Theta_0\right] = 0,$$

$$\phi_1 = \delta\phi_m \sin\left[\left(\frac{2\pi \cdot 1}{3}\right) + \Theta_0\right] = \delta\phi_m \cdot 0.866,$$

$$\phi_2 = \delta\phi_m \sin\left[\left(\frac{2\pi \cdot 2}{3}\right) + \Theta_0\right] = -\delta\phi_m \cdot 0.866. \qquad (9)$$
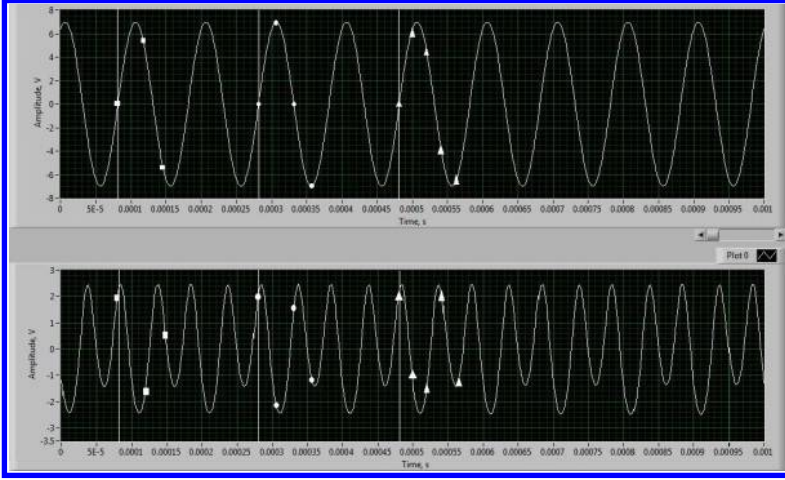
Fig. 2.   Acquisition points for the modulation signal (upper trace) and interference signal (lower trace) for different sampling rates.

Acquisition points for the case of $N = 4$ are marked with circles. According to the method modulation phase values are

$$\phi_0 = \delta\phi_m \sin\left[\left(\frac{2\pi \cdot 0}{4}\right) + \Theta_0\right] = 0,$$

$$\phi_1 = \delta\phi_m \sin\left[\left(\frac{2\pi \cdot 1}{4}\right) + \Theta_0\right] = \delta\phi_m,$$

$$\phi_2 = \delta\phi_m \sin\left[\left(\frac{2\pi \cdot 2}{4}\right) + \Theta_0\right] = 0,$$

$$\phi_3 = \delta\phi_m \sin\left[\left(\frac{2\pi \cdot 3}{4}\right) + \Theta_0\right] = -\delta\phi_m. \tag{10}$$

Acquisition points for the case of $N = 5$ are marked with triangles. According to the method modulation phase values are

$$\phi_0 = \delta\phi_m \sin\left[\left(\frac{2\pi \cdot 0}{5}\right) + \Theta_0\right] = 0,$$

$$\phi_1 = \delta\phi_m \sin\left[\left(\frac{2\pi \cdot 1}{5}\right) + \Theta_0\right] = \delta\phi_m \cdot 0.95,$$

$$\phi_2 = \delta\phi_m \sin\left[\left(\frac{2\pi \cdot 2}{5}\right) + \Theta_0\right] = \delta\phi_m \cdot 0.59,$$

$$\phi_3 = \delta\phi_m \sin\left[\left(\frac{2\pi \cdot 3}{5}\right) + \Theta_0\right] = -\delta\phi_m \cdot 0.59,$$

$$\phi_4 = \delta\phi_m \sin\left[\left(\frac{2\pi \cdot 4}{5}\right) + \Theta_0\right] = -\delta\phi_m \cdot 0.95. \tag{11}$$
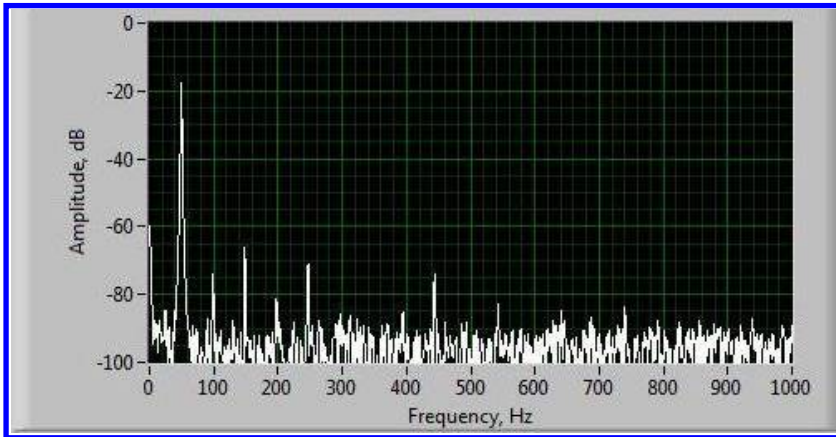
Fig. 3.   Spectrum of the sine-shape demodulated signal for $N = 3$.

As it was demonstrated in Ref. 6, for the proper calculation of target phase ϕ_S using triplet of samples $\{u^{(0)}, u^{(1)}, u^{(2)}\}$, three phase samples $\{\phi^{(0)}, \phi^{(1)}, \phi^{(2)}\}$ must have different values caused by the additional phase modulation. For example, for the case of $N = 4$ modulation triplet $\{\phi_0, \phi_1, \phi_3\}$ or $\{\phi_1, \phi_2, \phi_3\}$ with corresponding signal triplet must be picked out for calculation. In the same way, the rule of choosing phase samples can be formulated for other N.

For experimental testing of the method, sine, saw tooth and rectangular voltages were applied to a fiber-optic modulator to simulate the measured signal. The frequency of the test voltage was 50 Hz.

The demodulation method was implemented for the number of samples $N = 3, 4, 5$. As the results of the interference signals demodulation, the target signals $\phi_S(t)$ were extracted.

The spectrum of the sine-shape demodulated signal is shown in Fig. 3. This spectrum helps to evaluate such parameters as noise level and harmonic distortion. The noise level appears to be -90 dB, which corresponds to the minimal registered phase shifts of $3 \cdot 10^{-5}$ rad/Hz$^{1/2}$. The harmonic distortion for the sine signal for $N = 3$ was 0.5%.

Similar results were obtained for noise levels and harmonic distortions for other values of N and corresponding optimal modulation amplitudes.

4. Conclusion

The paper presents the experimental validation of the method of the interference signal demodulation with additional harmonic phase modulation and digital signal processing in LabVIEW.

The results of the implementation of the processing algorithms for $N = 3, 4, 5$ for various signal shapes demonstrated their effectiveness in application to the interference systems with signals described by Eq. (2).

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