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A Control Method to Eliminate Polarization-Induced Phase Distortion in Dual Mach-Zehnder Fiber Interferometer

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Abstract—**Polarization-induced Phase distortion happens in the distributed dual Mach-Zehnder fiber interferometric sensing system, which results in big locating errors. Based on the investigation in the cause, we propose and demonstrate a scheme using automatic polarization controller together with simulated annealing as control algorithm to obtain high positioning accuracy in the system. Through laboratory experiments, the key parameters of the algorithm are analyzed and the optimal settings of them are fixed. Field trial results show that this method can make a fast search for the optimal state of polarization and maintain the strong signal correlation for a long time.**

Keywords-Distributed sensor, polarization control, Mach-Zehnder fiber interferometer, polarization, simulated annealing

I. INTRODUCTION

With the exploitation of oil and gas resources as well as the surge in energy demand, the total pipeline mileage is growing constantly, and pipeline safety has become an important research topic. Our group has developed the distributed oil and gas pipeline leak detection and pre-warning system based on dual Mach-Zehnder Optical Fiber Interferometer for detecting and locating intrusions which may threaten pipeline safety[1]. Positioning the illegal invasion, as a key technology in the system, uses cross-correlation function to estimate time delay which requires strong correlation between signals. However, due to the phenomenon of polarization-induced fading which can cause phase distortion, correlation bewteen detection singals often degenerates and big locating errors then arise in pratical applications[2].

To solve the problem, passive phase demodulation method was studied in previous papers, in which the vibration phase signal are demodulated from every two original signals and thus avoid the negative effect of polarization-induced phase shift.[3] However, as this method costs much time in signal processing, it's hardly suitable in practical applications which demand good real-time performance. In this paper we propose and demonstrate a new method based on polarization control to eliminate phase distortion and furthermore to increase positioning accuracy of the system.

The existing polarization control algorithms mainly aim to eliminate the polarization mode dispersion(PMD) in the optical fiber and polarization dependent modulation(PDM) in the electrooptical modulator(EOM)[4],[5]. These feedback control algorithms are based on the peak value search of light intensity and can get control effect instantly with the output of control words. In the dual Mach-Zehnder interferometric system, however, the polarization control objective is the correlation between two detection signals which is not directly related to the light intensity. Therefore, the above mentioned algorithms can not apply to the pipeline security monitoring system. In this paper, the simulated annealing(SA) based on the correlation coefficient between two detection signals is employed as the polarization control algorithm to search for the input polarization operating point which results in little degeneration of detection signals' correlation. Field experiments show that the algorithm can rapidly find the operating point and continuously stabilize the correlation between the system detection signals.

II. RESEARCH ON THE CAUSE

Fig. 1 shows the equivalent optical path of the dual Mach-Zehnder fiber interferometer sensing system.

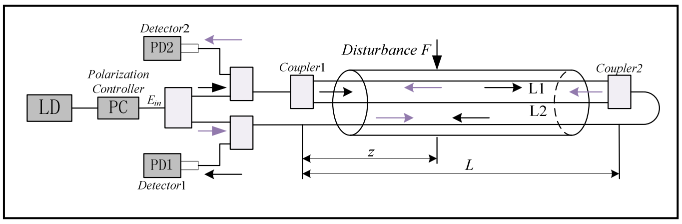

Figure 1. Conventional diagram of dual Mach-Zehnder system structure

The system input light can be represented by the Jones vector:

$$E_{in} = \begin{bmatrix} E_x \\ E_y \end{bmatrix} = E_0 \begin{bmatrix} \cos\theta\cos\varepsilon - j\sin\theta\sin\varepsilon \\ \sin\theta\cos\varepsilon + j\cos\theta\sin\varepsilon \end{bmatrix} \tag{1}$$

Where E_0 denotes the lightwave amplitude, θ and ε are the azimuth and ellipticity angle respectively which determine the input polarization state together.

Assuming that the forward and backward equivalent Jones Matrices of the two sensing arms are separately E_1,E_2 and E_1^T ,E_2^T which are determined by polarization property of the sensing fiber, the optical signals detected by photodetectors PD1 and PD2 can be represented by:

$$\begin{cases} E_{out1} = \left(E_1 + E_2 \cdot e^{j\delta(t)}\right) \cdot E_{in} \\ E_{out2} = \left(E_1^T \cdot e^{j\delta(t)} + E_2^T\right) \cdot E_{in} \end{cases} \tag{2}$$

Where $\delta(t)$ is the phase retardation difference between two sensor fibers caused by disturbance. The light intensity signals $I_1(t)$、$I_2(t)$ can be represented by:

$$\begin{cases} I_1(t) = \left|E_{out1x}\right|^2 + \left|E_{out1y}\right|^2 = I_0 \cos\left[\delta(t) + f_1(\theta,\varepsilon,\alpha)\right] \\ I_2(t) = \left|E_{out2x}\right|^2 + \left|E_{out2y}\right|^2 = I_0 \cos\left[\delta(t) + f_2(\theta,\varepsilon,\beta)\right] \end{cases} \tag{3}$$

Where I_0 is the light intensity of light source, α and β are the polarization induced phase shift caused by fiber birefringence respectively in forward and backward fiber path.

Taking the length of time t of the detected signals, the correlation coefficient between two channel signals is calculated by the following formula:

$$\rho_{xy} = \frac{\int_0^t I_1(t) I_2(t) dt}{\left[\int_0^t I_1^2(t)dt \int_0^t I_2^2(t)dt\right]^{\frac{1}{2}}} = \frac{\int_0^t \cos^2\left(\delta(t) + f_1(\theta,\varepsilon,\alpha)\right) \cdot \cos^2\left(\delta(t) + f_2(\theta,\varepsilon,\beta)\right) dt}{\left[\int_0^t \cos^2\left(\delta(t) + f_1(\theta,\varepsilon,\alpha)\right) dt \cdot \int_0^t \cos^2\left(\delta(t) + f_2(\theta,\varepsilon,\beta)\right) dt\right]^{\frac{1}{2}}} \tag{4}$$

The correlation coefficient ρ_{xy} is mainly determined by the phases of two detected signals, so it's feasible to alter the correlation between signals through changing the additional phase differences $f_1(\theta,\varepsilon,\alpha)$ and $f_2(\theta,\varepsilon,\beta)$. Since the additional phase difference are determined together by the input polarization state, the polarization property of fiber and the system laying environment in which the latter two are difficult to adjust artificially, it can only be changed by altering the input polarization state.

Fig. 2 shows the various interference light intensity in different input light polarization state which are respectively linearly polarized(θ=0.25π, ε=0), elliptically polarized(θ=0.25π, ε=0.25π), and circularly polarized(θ=0.25π, ε=0.125π) and $\delta(t)$ is assumed changing from -2π to 2π. From Fig 2, we can confirm that not only the amplitude but also the phase of the signal varies in different input polarization states. It's conceivable that there must be one input polarization state or several of them which can decrease the additional phase difference to an acceptable range. Therefore, it's feasible to improve the correlation between the detection signals by controlling the polarization state of input light and searching for the specific one as mentioned above.

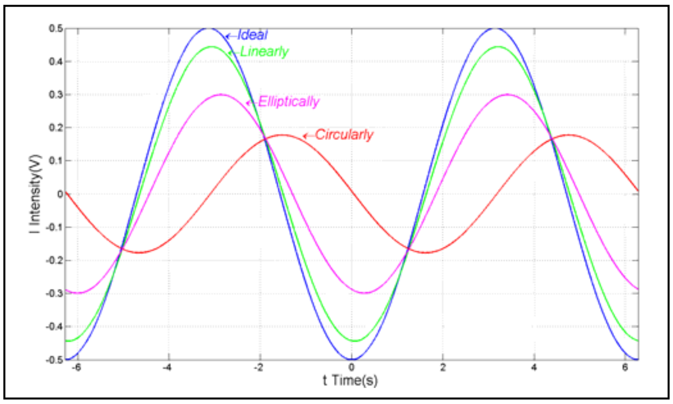

Figure 2. The interference light intensities in different input polarization states

III. ALGORITHM CLARIFICATION

A. *Algorithm Principle*

Setting correlation coefficient ρ_{xy} as the objective function, the polarization control model can be represented by:

$$\max(\rho_{xy}) = f(X) \qquad X \in \Theta \tag{5}$$

Where X denotes a combination of the polarization controller's retardation x_i(i=1,2,3,4). It's an optimization problem which requires global search capability of the control algorithm. simulated annealing[6]-[8] can probabilistically jump out of local optimum and achieve global optimum according to Metropolis criterion and thus is applied as the feedback control algorithm. The initial solution X_i is randomly generated whose objective function value is $f(X_i)$ and the new solution X_j is generated by state generator function whose objective function value is $f(X_j)$. The probability of accepting the new solution p_r is determined by the Metropolis criterion[7]:

$$p_r\left(X_i \Rightarrow X_j\right) = \begin{cases} 1 & f\left(X_j\right) \le f\left(X_i\right) \\ \exp\left(-\dfrac{f\left(X_j\right) - f\left(X_i\right)}{T_k}\right) & f\left(X_j\right) > f\left(X_i\right) \end{cases} \tag{6}$$

Where T_k is the current temperature state. Comparing p_r with a random number which ranges between 0 and 1, if p_r is larger, the new solution X_j is accepted, otherwise X_i is retained. After specified rounds of solution changing, local optimum polarization state under current temperature state can be found. Then T value is gradually reduced according to the temperature update function and local optimum solution under every temperature state can be derived. When T value is close to zero, calculation stops and current optimum solution is global optimum solution. The temperature update function is defined as:

$$T_{k+1} = p \cdot T_k \tag{7}$$

Where the temperature update coefficient p has a range of 0-0.95[8].

Since the phase retardation caused by polarization controller in practice has a range of 0-5π which means the solution space is bounded. We define the state generator function as follows:

$$X_{i+1} = \begin{cases} X_i - f(X_i) \cdot s & X_i \geq 5\pi \\ X_i + f(X_i) \cdot c \cdot s & 0 < X_i < 5\pi \\ X_i + f(X_i) \cdot s & X_i \leq 0 \end{cases} \tag{8}$$

Where s is searching step size, c is plus or minus one randomly.

B. Setting of Key Parameters

Simulated annealing algorithm performance does not rely on the value of initial solution but can be affected by settings of key parameters such as the initial temperature T_0, the search step size s in the state generator function and the temperature update coefficient p.

In order to obtain the optimum setting of key parameters so as to ensure the global search capability of the control algorithm, experiments have been carried out to test the optimization in different parameter settings.

Fig. 1 shows the installation position of the polarization controller which can control both the forward and backward optical path and avoid changing the system structure as well. The model of the polarization controller applied is polaRITE Ⅲ from General Photonics.

1) The choice of the initial temperature

In simulated annealing algorithm, higher initial temperature T_0 will enhance the probability of obtaining high quality solution but increase the number of outer loop at the same time. With comprehensive consideration of both quality and efficiency of optimization, the range of T_0 is set less than one.

Fig. 3 shows the different search areas in Poincare Sphere with different initial temperature settings in stimulated annealing algorithm. When T_0 is small, the algorithm can only search part of the region in Poincare Sphere with a large blind area. According to the experiment results, the initial temperature is set as 1.

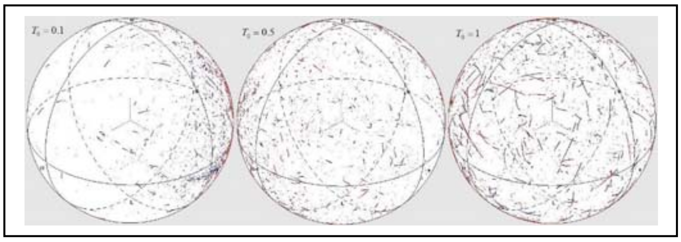

Figure 3. Initial temperature effect on search area, T_0=0.1,0.5,1.

2) The choice of temperature update coefficient

Simulated annealing is a process of temperature slowly decreasing in which higher value of temperature update coefficient p will bring about a larger searching area but lower convergence rate .

Fig. 4 shows the different search areas in Poincare Sphere with different settings of p in stimulated annealing process. Since they do not have much difference as Fig. 4 shows, taking into account that the higher value of p will slow down the convergence speed and then degrade the real-time performance of the system, the temperature update coefficient is set as 0.5.

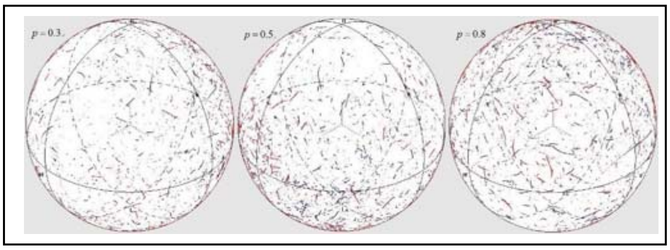

Figure 4. Temperature update coefficient effect on search area, p=0.3,0.5,0.8.

3) The choice of search step size

State generator function determines whether the system can search for the optimal value in the whole solution space. Large step size brings about big change of the solution which may deviate from the solution space, while small one brings about little change of the solution which can hardly jump out of local optimum to achieve global optimum.

Fig. 5 shows the effects of different settings of search step size. When s increases to 1.10 can it jump out of local optimum and search the whole Poincare Sphere. Therefore, s is set as 1.10.

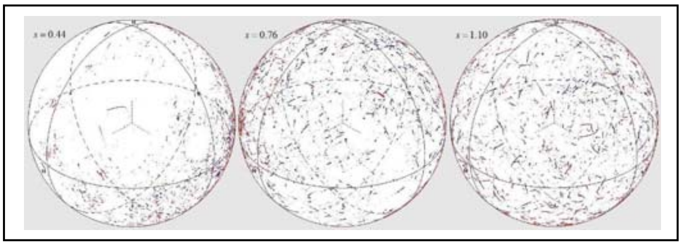

Figure 5. Search step size effect on search area, s =0.44,0.76,1.10.

IV. FIELD EXPERIMENT VERIFICATION

The approach is applied in the oil pipeline safety monitoring and pre-warning system which covers a monitoring distance of 43km.

Fig. 6 shows the contrast between the original detection signal waveforms with and without employment of the polarization control method. When the approach is not applied, the signals in Fig. 4(a) has a calculated correlation coefficient ρ_{xy} =0.28, with employment of the polarization control approach, the correlation coefficient is 0.95 as shown in Fig. 4(b).

Fig. 7 shows the correlation coefficient between detection signals within 24 hours recorded every second after using the polarization control method. which verifies the stability of the approach.

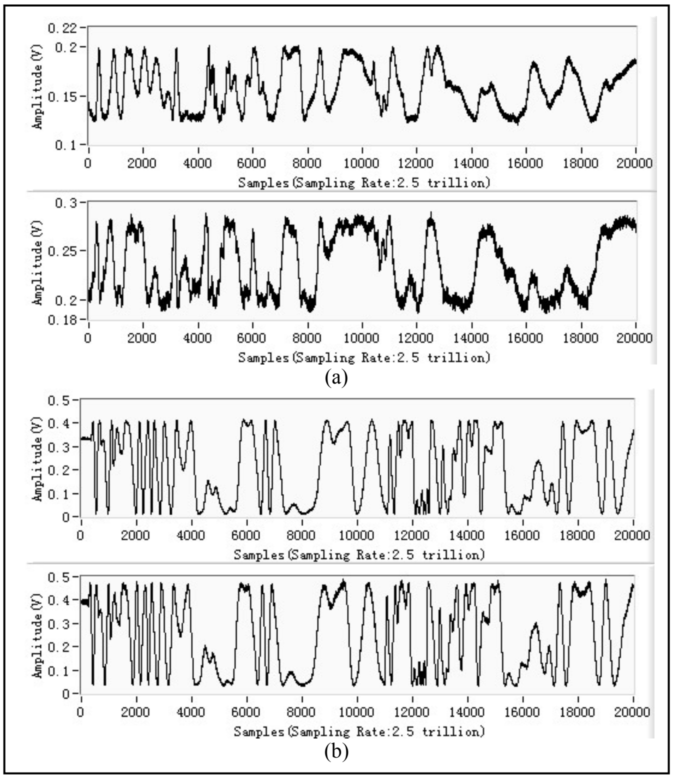

Figure 6. Origianl detection signal waveforms. (a)Polarization control is not applied. (b)Polarization control is applied.

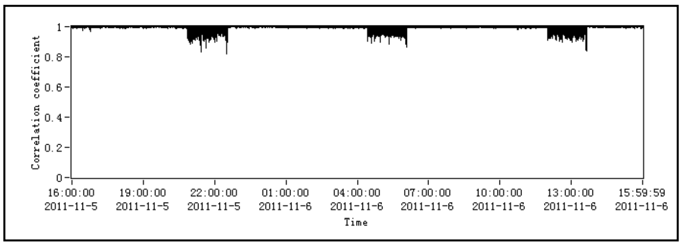

Figure 7. Correlation coefficient within twenty-four hours under polarization control.

V. CONCLUSION

Based on the investigation in the cause of positioning errors, we present a new approach to solve the degeneracy problem of detection signals' correlation in the distributed dual Mach-Zehnder fiber interferometric sensing system using automatic polarization controller together with simulated annealing as control algorithm. Using correlation coefficient between two detection signals as the feedback quantity, this method can control the input polarization state in real-time and find the operating point rapidly when the correlation between signals degenerates. Through laboratory experiments, the key parameters of the algorithm are analyzed and the optimal settings of them are fixed. Field trial shows significant improvement and stability of the correlation between detection signals after employing the approach.

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