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Spectrum parameter estimation in Brillouin scattering distributed temperature sensor based on cuckoo search algorithm combined with the improved differential evolution algorithm

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ABSTRACT

In the distributed optical fiber sensing system based on Brillouin scattering, strain and temperature are the main measuring parameters which can be obtained by analyzing the Brillouin center frequency shift. The novel algorithm which combines the cuckoo search algorithm (CS) with the improved differential evolution (IDE) algorithm is proposed for the Brillouin scattering parameter estimation. The CS-IDE algorithm is compared with CS algorithm and analyzed in different situation. The results show that both the CS and CS-IDE algorithm have very good convergence. The analysis reveals that the CS-IDE algorithm can extract the scattering spectrum features with different linear weight ratio, linewidth combination and SNR. Moreover, the BOTDR temperature measuring system based on electron optical frequency shift is set up to verify the effectiveness of the CS-IDE algorithm. Experimental results show that there is a good linear relationship between the Brillouin center frequency shift and temperature changes.

1. Introduction

In the past decade, continuous distributed optical fiber sensing technology based on the Brillouin scattering has developed rapidly. It attracts considerable research interest due to its excellent capability to provide a measured property of interest, such as strain and temperature [1]. The distributed fiber sensors technology based on Brillouin scattering has many advantages, including high accuracy, high spatial resolution, long measuring distance, and so on. In Brillouin optical time domain reflection (BOTDR) system, how to obtain the relative Brillouin frequency shift with a higher accuracy is the key. In order to obtain the Brillouin frequency shift, many scholars have proposed different algorithms to extract the Brillouin spectrum features. For example, Chuankai et al. [2] have optimized the model parameters with Levenberg–Marquardt (LM) algorithm, and analyzed the nonlinear theoretical models of the Brillouin spectrum in the BOTDR temperature sensing system. Kleefeld and Rei [3] have used the LM algorithm for parameter estimation and the numerical results demonstrate that some desired parameters can be reconstructed. Li Yongqian [4] has proposed a fast and high accurate initial values obtainment method, the proposed method fixes the problem of fast and high accurate parameter estimation for Brillouin scattering. Our research team [5] has proposed an improved Newton algorithm based on finite element analysis for extracting the Brillouin scattering spectrum features, and this algorithm has high accuracy to extract the feature of Brillouin scattering spectrum with different linewith and SNR. These previously proposed algorithms have good operational precision and can achieve spectrum parameter estimation in Brillouin scattering distributed temperature sensor. However, to improve the spatial resolution and temperature resolution of the sensor, a novel algorithm with better operational precision should be required.

To obtain higher precision, the CS-IDE method which combines the cuckoo search (CS) algorithm with the improved differential evolution (IDE) algorithm is proposed. The application of the CS-IDE algorithm in fitting the Brillouin scattering spectrum is discussed. The estimated parameter values are comparatively accurate by the CS-IDE algorithm in BOTDR system. The experimental results show that it can improve the measurement precision and can provide guidance for the development of high precision distributed optical fiber sensor.

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2. The principle

2.1. The BASIC principle

For the Brillouin scattering in optical fiber, the exponential decay of acoustic waves results in a Brillouin scattering spectrum, which presenting a Lorenzian spectral profile [6,7]

$$g_{B(\nu)} = g_0 \frac{(\Delta\nu_B/2)^2}{(\nu - \nu_B)^2 + (\Delta\nu_B)^2} \tag{1}$$

where ν is the Brillouin frequency, ν_B is the Brillouin center frequency shift, which is the difference between the central frequency of Brillouin scattering spectrum and the frequency of incident light. $\Delta\nu_B$ is the full-width at half maximum (FWHM), g_0 is the peak value of Brillouin gain spectrum.

However, the Lorentzian spectral profile of Brillouin scattering can become a Gaussian curve by reason of some factors, including the short pulse interaction in Brillouin scattering, low extinction ratio, natural broadened Brillouin scattering spectrum, Doppler broadening and so on [7,8]. Thus, a new matching function of Brillouin scattering spectrum is represented by combining the Lorentzian and Gaussian functions with the linear weight ratio k, the improved function [9] is shown as follows

$$f_B(\nu) = k\frac{\left(\Delta\nu_{B1}/2\right)^2}{(\nu - \nu_B)^2 + \left(\Delta\nu_{B1}/2\right)^2} + (1 - k)\exp\left[-2.773(\nu - \nu_B)^2/\Delta\nu_{B2}^2\right] \tag{2}$$

where the first half of function represents Lorentzian function curve, and the latter part represents Gaussian function curve. k $(0 < k < 1)$ is Pseudo-Voigt shape factor (Fully Lorentzian: $k = 1$; Fully Gaussian: $k = 0$), which represents the linear combination degree between the Lorentzian function and Gaussian function, $\Delta\nu_{B1}$ and $\Delta\nu_{B2}$ are the Lorentzian and Gaussian spectral linewidth, respectively.

In the BOTDR system, strain and temperature can be obtained from Brillouin center frequency shift according to the following relationship [10]

$$\begin{cases} \delta T = \delta\nu_B/C_{\nu T} \\ \delta\varepsilon = \delta\nu_B/C_{\nu\varepsilon} \end{cases} \tag{3}$$

where δT is the temperature resolution, $\delta\varepsilon$ is the strain resolution, $C_{\nu T} = 1.10 \pm 0.02$ MHz/K is the temperature coefficient of Brillouin frequency shift, $C_{\nu\varepsilon} = 0.04863 \pm 0.0004$ MHz/με is the strain coefficient of Brillouin frequency shift, and $\delta\nu_B$ is the minimum measurement of Brillouin frequency shift.

2.2. The CS-IDE algorithm

Supposed the fitting of Brillouin scattering spectrum is

$$y = f_B(x_i\ , A_i) \tag{4}$$

where $A_i = (A_1,\ A_2,\ \cdots A_3)^T$ is the estimated parameters vector including k, ν_B, $\Delta\nu_{B1}$ and $\Delta\nu_{B2}$, i is the number of estimated parameters. The parameter estimation problem is to minimize as

$$r_i^2 = \sum_{j=0}^{m-1}\left[y_i - f_B(x_i, A_i)\right]^2 \tag{5}$$

where y_i is the experimental data point, and $f_B(x_i, A_i)$ is the amplitude of fitting curve corresponding to A_i.

When the variance r^2 between the experimental data and fitting curve is minimized, the fitting degree is highest. The frequency corresponding to the peak of basis function is the actual frequency shift of Brillouin scattering spectrum. When the temperature or strain leads to Brillouin frequency drift, the scattering spectrum data changes as well as the scattering center frequency corresponding to the peak of basis functions. Therefore, the frequency shift of basis function can be obtained by Brillouin frequency offset.

2.2.1. The principle of CS algorithm

The CS algorithm simulates the random path of cuckoo to find a suitable spawning nest. Firstly, initialize the bird's nest location randomly in the space of feasible solution and calculate the fitness value of each nest location. Secondly, keep the optimal fitness value of nest location to the next generation and enter into the iterative process of nest location. Thirdly, evaluate the fitness of each nest to determine the optimal location of current generation of each nest and the global optimum position. Finally, update the location according to the following equation [11–13]

$$x_i^{t+1} = x_i^t + a \oplus Levy(\lambda)\ \ (i = 1,\ 2,\ \cdots,\ N) \tag{6}$$

where $x_i^t = (x_{i1}^t, x_{i2}^t, \cdots, x_{id}^t)$ is the bird's nest location, $x_i^t = (\nu_B,\ \Delta\nu_{B1},\ \Delta\nu_{B2},\ k)$ is the estimated parameters vector corresponding to Eq. (2), t is the generation, i $(i = 1, 2, \cdots, N)$ is the number of bird's nest, N is the total number of the bird's nest, d is the dimension of search space, a is the variable step size, the product $\oplus$ means entry-wise multiplications and $Levy{\sim}u = t^{-\lambda}(1 < \lambda \le 3)$ is the search path.

It can be get the local optimal solution $x_i^t = (\nu_B,\ \Delta\nu_{B1},\ \Delta\nu_{B2},\ k)$ by Eq. (6) of CS algorithm. But CS algorithm fall into local optimum easily, the solution of the CS algorithm can not be the global optimal solution.

2.2.2. The principle of IDE algorithm

Differential evolution (DE) algorithm is an efficient and powerful population-based stochastic search technique to solve the optimization problems. The solution can be obtained by the DE algorithm, but in order to extract higher accuracy solutions, the improved DE (IDE) algorithm which is based on variable step size gradient algorithm is proposed in this paper. The IDE algorithm with better adaptability, the step of iteration is updated dynamically according to the previous generation iteration results. Therefore, the search speed and optimization accuracy are improved greatly to a certain extent. The specific procedures are described below. Firstly, generate the initial population randomly. Secondly, conduct mutation, crossover and selection. Thirdly, keep the best individual and eliminate the inferior individuals according to the fitness of every individual. Finally, guide the search process approaching to an optimal solution. The steps above are repeated generation after generation until some specific termination criteria are satisfied.

The preferred method to solve the problem in the application of DE algorithm is the strategy of DE/rand/1 [14–17]. The iterative formula with variable step size is as follows:

$$\nu_i^t = x_{r1}^t + \mu F(x_{r2}^t - x_{r3}^t) \tag{7}$$

where $\nu_i^t = (\nu_{i1},\ \nu_{i2},\ \cdots,\ \nu_{id})$ is the random vector, and $\nu_i^t = (\nu_B,\ \Delta\nu_{B1},\ \Delta\nu_{B2},\ k)$ is the estimated parameters vector corresponding to Eq. (2), $\nu_i^t = (x_{i1},\ x_{i2},\ \cdots,\ x_{id})$ is the target vector, $r_1, r_2, r_3 \in \{1, 2, \cdots N\}$ are the random number, $F \in [0, 2]$ is the weighted factor and μ is the variable step size.

The new species produce according to the following equation

$$x_{ij}' = \begin{cases} \nu_{ij}, & rand(j) \le CR\ \ or\ \ j = rand(i) \\ x_{ij}, & rand(j) \ge CR\ \ or\ \ j \ne rand(i) \end{cases} \tag{8}$$

where $j \in [1, D]$ is the number, $rand(j) \in [0,\ 1]$ is the value produced by the same random number generator, $CR \in [0,\ 1]$ is the