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An accurate and rapid method for extracting parameters from multi-peak Brillouin scattering spectra

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ABSTRACT

To improve the accuracy of the simultaneous measurement of temperature and strain from Brillouin scattering, an accurate and rapid method for extracting parameters from multi-peak Brillouin scattering spectra is proposed. First, a Brillouin scattering spectrum that contains multiple peaks is segmented into several single-peak signals. Second, approaches such as linear least-squares fitting are used to obtain the initial values for the parameters of the Brillouin scattering spectrum. Finally, the Levenberg–Marquardt algorithm is used to minimize the objective function based on a nonlinear least-squares fit. The proposed method and three other typical methods are implemented and applied to simulated signals with different signal-to-noise ratios and to two real signals acquired by a Brillouin optical time-domain reflectometer. The results reveal that the random method easily diverges. The harmonic reconstruction method is sensitive to noise. The individual peak fitting method has significant errors when it is applied to multi-peak signals. However, the proposed method rapidly converges to the optimal solution and is the most accurate of the four methods. The proposed method solves the problem of extracting parameters from multi-peak Brillouin scattering signals rapidly and with high accuracy. Additionally, the proposed method provides the technical capability to simultaneously measure temperature and strain.

1. Introduction

Over the past two decades, the process of Brillouin backscattering in fibres has been widely investigated and is the basis for distributed temperature and strain measurements [1–3]. The dependences of both the Brillouin frequency shift and the intensity of the spontaneous Brillouin signal on strain and temperature have formed the basis of such measurements. However, the measurement range and resolution are primarily limited by the accuracy of the intensity measurement [4]. The accuracy of the Brillouin frequency shift [5] measurement is high, but it is difficult to address the cross sensitivity [5] of the Brillouin frequency shift to both temperature and strain, and determining whether the change is caused by temperature or by strain is very difficult.

A good method for solving the above problem is to use a multi-peak Brillouin spectrum, in which each peak's Brillouin frequency shift has different dependences on temperature and strain [4–9]. In [4], the first and second Brillouin peaks of a LEAF (Large Effective Area Fibre) fibre with a length of 3682 m are used to achieve a temperature resolution of 5 °C, a strain resolution of 60 $\mu\epsilon$ and a spatial resolution of 2 m. This method is an elegant and exciting approach. Subsequently, in [5], the sensing length is extended to 22 km, and the temperature and strain errors are 27 °C and 570 $\mu\epsilon$, respectively. These errors are significant because the differential frequency change for the first two peaks is approximately 190 kHz/°C [6], which imposes a very high requirement on the frequency resolution. In a Brillouin optical time-domain reflectometry (BOTDR) system, frequency resolution in the kHz range is very difficult to achieve because of the weak Stokes signal and significant computations. Precisely and rapidly acquiring a Brillouin scattering spectrum is a formidable challenge in terms of the system setup and spectral fitting. Although many papers describe the simultaneous measurement of temperature and strain from a multi-peak Brillouin spectrum [4–8], only a few papers describe a method for extracting the multi-peak parameters [9–15]. In [9], multi-peak parameters are obtained by fitting all single-peak signals from the multi-peak spectrum. However, the method for segmenting the signal is not presented in the published papers and, more importantly, the accuracy of the method is not investigated. Refs. [10–12] present a method for extracting multi-peak parameters. In this method, the objective function is optimized by the Levenberg–Marquardt algorithm, and the parameters are readily extracted. However, the method for obtaining the initial values,

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which have a considerable influence on the accuracy and computational burden in the extraction of parameters, is not presented in this paper. The harmonic reconstruction method [13] uses a harmonic to fit the multi-peak spectrum. This method may possess high accuracy for noise-free signals. However, noise is inevitable in real Brillouin signal measurements and affects the accuracy of the simultaneous measurement of temperature and strain. Therefore, an accurate and rapid method for extracting parameters from a multi-peak Brillouin spectrum is urgently needed.

To overcome this problem, a method for data segmentation, a method for obtaining the initial values of the parameters of the Brillouin scattering spectrum and the formulation and solution of the objective function for the multi-peak Brillouin scattering spectrum are investigated. From the results of the analysis, a method for extracting parameters (the gain, linewidth and central frequency of each peak) from multi-peak Brillouin scattering spectra is proposed. Analyses of the numerically generated and the real multi-peak Brillouin scattering spectra reveal that the proposed method can rapidly and accurately extract the parameters for multiple peaks.

2. Theory of simultaneous measurement of temperature and strain

When a small fraction of incident light is inelastically scattered by thermally excited acoustic waves (acoustic phonons) in an optical fibre, spontaneous Brillouin scattering will occur. A periodic modulation of the dielectric constant and the refractive index of the medium is generated because of the density variations caused by the acoustic wave. The scattered light undergoes a Doppler frequency shift, and the greatest scattering is in the backward direction. The above Doppler frequency shift is also known as the Brillouin frequency shift. The strong attenuation of sound waves in silica determines the shape of the Brillouin gain spectrum. When the injection pulse width is greater than 10 ns, the exponential decay of the acoustic wave results in a gain $g_B(\nu)$ described by a Lorentzian spectral profile [10,14]:

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

where ν represents frequency (GHz) and ν_B represents the Brillouin frequency shift (GHz), which characterizes the difference between the central frequency of the Brillouin scattering spectrum and the frequency of the incident light. The Brillouin frequency shift for a single-mode optical fibre is generally approximately 11 GHz when the wavelength of the incident light is 1550 nm. $\Delta\nu_B$ represents the full width at half maximum (FWHM) bandwidth (GHz) of the Brillouin scattering spectrum and is relevant to the lifetime of phonons, and g_0 represents the maximum value of the Brillouin gain spectrum.

If an optical fibre has a core with a compound composition, such as a LEAF (Large Effective Area Fibre), photonic crystal fibre or SMF −28e+, more than one Brillouin scattering-active acoustic mode exists in the fibre; therefore, the Brillouin spectrum contains multiple peaks [15]. The exponential decay of every acoustic-mode wave is described by a Lorentzian spectral profile [16]; thus, the multi-peak Brillouin spectrum can be expressed as:

$$g_{BT}(\nu) = \sum_{i=1}^{M} g_{0,i} \frac{(\Delta\nu_{B,i}/2)^2}{(\nu-\nu_{B,i})^2 + (\Delta\nu_{B,i}/2)^2} \tag{2}$$

where $\nu_{B,i}$ represents the Brillouin frequency shift (GHz) of the ith peak and characterizes the difference between the central frequency of the ith Brillouin scattering spectrum and the frequency of the incident light, $\Delta\nu_{B,i}$ represents the 3 dB bandwidth (GHz) of the Brillouin scattering spectrum of the ith peak, $g_{0,i}$ represents the maximum value of the Brillouin gain of the ith peak, and M denotes the number of peaks.

The Brillouin frequency shift for every pair of peaks in the optical fibre has different dependences on temperature and strain, and the relation is given by:

$$\begin{bmatrix} \delta\nu_{Bm} \\ \delta\nu_{Bn} \end{bmatrix} = \begin{bmatrix} C_{Tm} & C_{\epsilon m} \\ C_{Tn} & C_{\epsilon n} \end{bmatrix} \begin{bmatrix} \Delta T \\ \Delta\epsilon \end{bmatrix} \tag{3}$$

where $\delta\nu_{Bm(n)} = \nu_{Bm(n)}(\epsilon, T) - \nu_{Bm(n)}(\epsilon_0, T_0)$ is the increment of the Brillouin frequency shift. $\nu_{Bm(n)}(\epsilon, T)$ denotes the mth (nth) peak's Brillouin frequency shift corresponding to strain ϵ and temperature T. ϵ_0 and T_0 are the strain and temperature, respectively, that correspond to a referenced Brillouin frequency shift. $\Delta\epsilon = \epsilon - \epsilon_0$ denotes the difference in the strain, and $\Delta T = T - T_0$ denotes the difference in the temperature. $C_{\epsilon m(n)}$ and $C_{Tm(n)}$ denote the strain coefficients and the temperature coefficients for the mth and nth peaks, respectively, and they satisfy:

$$\begin{vmatrix} C_{Tm} & C_{\epsilon m} \\ C_{Tn} & C_{\epsilon n} \end{vmatrix} \neq 0 \tag{4}$$

After solving Eq. (3), the change in temperature, ΔT, can be determined from:

$$\Delta T = \frac{\delta\nu_{Bn}C_{\epsilon m} - \delta\nu_{Bm}C_{\epsilon n}}{C_{\epsilon m}C_{Tn} - C_{\epsilon n}C_{Tm}} \tag{5}$$

Similarly, the change in the fibre strain, $\Delta\epsilon$, can be obtained from:from Eqs. (5)–(6), we observe that the simultaneous extraction of the Brillouin frequency shifts for two peaks is required to simultaneously measure temperature and strain. Because the signals for these peaks will interfere with each other, to improve the accuracy in extracting the parameters of the Brillouin scattering spectrum, all of the peaks should be considered in the objective function. Consequently, all of the peaks should be considered for not only segmenting the signal but also for obtaining the initial values and for minimizing the objective function.

3. Segmentation of the multi-peak Brillouin scattering signal

The initial values of the Brillouin scattering spectrum parameters have significant effects on the optimization of the corresponding objective function. These initial guesses should be obtained more quickly and more accurately. Therefore, the multiple peaks of the Brillouin scattering signal should be segmented into multiple single-peak signals beforehand. The peak value and trough value can be used to determine any individual peak range. That is, two consecutive trough values are used to determine an individual peak, and at the same time, the signal between the two consecutive trough values only has one peak value. In this paper, the peak value is defined as follows:

Assume that ν_i is the ith scanned frequency, where $i = 1, 2, \ldots, N$. Q is a positive integer. If for any i and j ($Q+1 \le i \le N-Q$, $-Q \le j \le Q$) Eq. (7) is fulfilled, then $[\nu_i, g_B(\nu_i)]$ is a peak.

$$g_B(\nu_i) \ge g_B(\nu_{i+j}) \tag{7}$$

If for any i and j ($Q+1 \le i \le N-Q-1$, $-Q \le j \le Q$) Eq. (8) is fulfilled, then $[\nu_i, g_B(\nu_i)]$ is a trough.

$$g_B(\nu_i) \le g_B(\nu_{i+j}) \tag{8}$$

If the signal-to-noise ratio (SNR) is not too low, the value of Q can be easily determined. At this point, once Q is set to a suitable value, the obtained peak values and trough values are close to the corresponding real values, and the segmented peaks can be used. In