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Reconstruction of distributed strain profile using a weighted spectrum decomposition algorithm for Brillouin scattering based fiber optic sensor

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Abstract—Brillouin scattering based fiber optic strain sensor is used to measure distributed strain profile of a structure for structural health monitoring. A distributed strain profile is derived from the Brillouin spectrum peaks but error is induced when a local strain change occurs in a distance scale smaller than the spatial resolution. In this study, a new algorithm is proposed to reconstruct a Brillouin spectrum by eliminating low qualified data from the raw spectrum data. This is achieved by evaluating the strain gradient profile and statistically decomposing the power, width and peak frequency of the raw spectrum data. This algorithm is versatile because it can be applied to various strain shapes and magnitudes. The reliability of the algorithm is verified experimentally by showing that the error of the strain profile obtained using the new method becomes 25% of that using the conventional peak detection method.

Index Terms—Optical fiber sensors, Strain measurement, Data analysis, Spectrum decomposition, Brillouin optical time domain reflectometry, error reduction

I. INTRODUCTION

As a method of structural health monitoring, Brillouin optical time domain reflectometry (BOTDR) is used for distributed strain measurement of a structure attached with fiber optic sensor. The distributed strain profile of the structure is obtained from the measured spectral distribution, which is a convolution of the natural Brillouin gain distribution with a pulse spectrum [1]. Because the lifetime of phonon is about 8ns in silica fiber, the pulse width has a limitation of 10 ns [2]. Therefore, the spatial resolution of a typical BOTDR interrogator is about 1m [3-4].

When the true strain profile varies within the given spatial resolution (like a crack or a sudden spatial change in strain), the Brillouin spectrum becomes distorted or contains additional peaks [5]. As the measured Brillouin spectrum is a superposition of all spectrum components with different peak frequencies, evaluating the peak frequency of the superposed

spectrum becomes difficult [6]. This in turn induces error in evaluating distributed strain when compared to the true strain profile [5]. Some of the previous research exploit algorithms such as 3D image restoration to reduce the Brillouin spectrum white noise [7-8]. However, the spectrum distortion induced systematic error has not yet been thoroughly investigated.

Because the Brillouin backscattered spectrum detected by a BOTDR interrogator is characterized as the convolution of Lorentzian distribution function with the launched pulse power [9], measurement is simplified as a weighted average strain value over its spatial resolution [10-11]. For a Gaussian shape input pulse, the weight function follows a normal distribution and its width increases with strain [12]. By de-convoluting the measured strain using the strain-dependent weight function, it is possible to reconstruct a distributed strain profile close to the true values [13]. However, this weight function must be defined at different strain levels, which leads to complex evaluation process.

In this study, instead of evaluating the weight functions for different strain levels, we use a 3-D spectrum decomposition approach as an alternative data reconstruction algorithm. We firstly show an optics model that fits BOTDR strain measurements at different strain levels with one weight function. Using this model, a relationship between data reliability and strain gradient is obtained. The Brillouin spectrum is then reconstructed by an inverse analysis algorithm and an improved distributed strain profile is deduced. The reliability of the proposed algorithm is verified by laboratory tests.

II. PROBLEM FORMULATION

The frequency shift of a Brillouin backscattering signal is related to localized acoustic wave and thus depends on the strain and temperature along the fiber [14]. In the BOTDR system, the Brillouin backscattering power $\mathbf{dP_B}(\mathbf{z}, \mathbf{v})$ can be expressed by the following equations in a small section of the fiber [3].

[†]This paragraph of the first footnote will contain the date on which you submitted your paper for review.

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$$dP_B(z, \nu) = B(\nu, \nu_B) \left(\frac{c}{2n} \right) P(z) dx \times \exp(-2\alpha_z z) \quad (1)$$

$$B(\nu, \nu_B) = \frac{h(\frac{\omega}{2})^2}{(\nu - \nu_B)^2 + (\frac{\omega}{2})^2} \quad (2)$$

$$z = ct/(2n) \quad (3)$$

where P is the launched pulse power, c is the light velocity in vacuum, n is the fiber refractive index, α_z is the attenuation coefficient of the fiber, z is the scattering position, and $B(\nu, \nu_B)$ is the Brillouin gain spectrum with a Lorentzian shape defined by Equation (2). ν_B is the center frequency at which $B(\nu, \nu_B)$ has a peak power of h , and ω is the full width at half-maximum (FWHM) of $B(\nu, \nu_B)$.

The spatial resolution of the BOTDR system is governed by the minimum length that the interrogator can discriminate between two adjacent locations having different strains (or temperatures). Since the received backscattered Brillouin signal is the convolution of the linewidth of the Brillouin spectrum with an input light pulse, the length of the pulse determines the spatial resolution of the interrogator. This can be calculated as $L = \tau v_g/2$, where τ is the pulse width and v_g is the group velocity of the light pulse.

When a strain change occurs in a distance scale smaller than the spatial resolution, the measured strain value becomes different from the true value and the strain profile appears as a spread one. This leads to systematic measurement error. In the next section, we will examine this type of error.

III. MEASUREMENT SYSTEMATIC ERROR

In this section, an analytical model is derived to simulate BOTDR measurements of a step change of strain at different strain levels. The solution is then used to model measurements at different strain levels. We show that the systematic measurement error of BOTDR increases with strain gradient. The relationship between error value and strain gradient is then derived based on the model.

A. Measurement simulation

For a commercial BOTDR interrogator with an unknown input pulse and unidentified signal processing method, the output Brillouin spectrum is often simulated as a weighted average spectrum over the spatial resolution of the interrogator. Assume that there is a Brillouin spectrum profile (P_B) with a step center frequency shift occurring in a distance scale smaller than the spatial resolution. At a particular sampling point z and a particular frequency ν , the measured Brillouin power $P_{MB}(z, \nu)$ will be an integration of $P_B(x, \nu)$ (Eq. 4) with a weight function $g(x)$ (Eq. 5), which has a normal distribution shape with width (σ) (0.105m for Neubrescope NBX-5000 interrogator used in this study). $x \in (z - \frac{L}{2}, z + \frac{L}{2})$ represents all data points within the spatial resolution (L).

The graphical illustration of the convolution between natural Brillouin spectrum and the weight function is given in Fig. 1. Fig. 1 (a) shows the Brillouin spectrum $P_B(x, \nu)$, whereas Fig. 1 (b) shows the weight function $g(x)$ at each location x .

$$P_{MB}(z, \nu) = \int_{z-L/2}^{z+L/2} P_B(x, \nu) g(x) dx \quad (4)$$

$$g(x|z, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-z)^2}{2\sigma^2}} \quad (5)$$

The Brillouin spectrum can be expressed by Eqs. (4) and (5) based on the assumptions that (i) there is negligible pump depletion and fiber loss, so that the maximum gain in each section is the same as the other sections, and (ii) the power of spontaneous Brillouin scattering is linearly proportional to the energy of the optical pulse.

Figure 1 (a) Brillouin spectrum profile (P_B) and (b) the distribution of P_B at frequency ν .

B. Model validation

The reliability of the model was validated by conducting a series of laboratory test where a section of 1.5m optics fiber was fixed at one end and stretched at the other end. Measurements were taken at three different levels (around 1400 $\mu\epsilon$, 2200 $\mu\epsilon$ and 3000 $\mu\epsilon$) by Neubrescope NBX-5000 interrogator. The tested strain sensing cable was made by the Fujikura Ltd, which had four single-mode optical fibers embedded in the middle of the cable and two steel wires on sides to reinforce the cable. As the experiments were done in a temperature constant lab (20°C $\pm$ 0.5°C), the temperature effect is not considered here. Fig. 2 shows the comparison of strain input data, simulated strain results using Eq. (4) & (5), and interrogator measurements. A good agreement between the simulation and experimental values can be clearly observed in the figure.

Figure 2 The comparison of simulated results, interrogator measured results at different strain input levels.

Fig. 2 also implies that systematic error is more significant at large strain change sections (Distance = 0.75m-1.25m and 2.25m-2.75m). For a BOTDR interrogator with a certain spatial resolution L ($L=1$ meter is used in simulations), a non-uniformly distributed strain over L distorts the received Brillouin spectrum or induce additional peaks to the spectrum. As a result, strain measurement contains a larger system error at points where strain is changing rapidly spatially (i.e. a step change).

C. Systematic error characterization

Based on the experimental data shown in Fig. 2, the spatial resolution related spectrum deformation induced systematic errors are calculated by comparing the measured strain and strain input. The strain gradient is calculated by the measured strain and distance. The error and strain gradient relationship is shown in Fig. 3. For each strain level, the error increases when the strain gradient increases, and it is positive because the measured strain is greater than the applied true strain. Then the error reduces when the strain gradient is close to the maximum where the measurement strain line crosses the strain input line in Fig. 2. After the crossing point, the strain gradient decreases to zero, and the error decreases with negative value because the measured strain is smaller than the applied true strain. In general, an approximately linear relationship between error and strain gradient is obtained. This approximately linear relationship implies that the strain gradient can be used for data reliability quantification.

Figure 3 The systematic error with strain gradient obtained from Fig.2.

IV. DATA INTERPRETATION

In the newly proposed data interpretation algorithm, the 3D Brillouin spectrum is decomposed using the regularization method. During this process, the measured strain gradient profile is used to represent data quality.

A. Estimation of the spectrum power

It was verified in the previous section that the Brillouin spectrum can be calculated as the integration of the local Brillouin spectrum data with a weight function over interrogator's spatial resolution at each frequency level. Therefore, the main objective of the proposed back-analysis

algorithm is to decompose the received Brillouin power with the weight function along the cable distance at each frequency level.

For a given interrogator, it has $g(x)$ as a weighted function at each location. When a measurement is taken, there is a window determined by a pulse with n is moving along the fiber. The power of the weighted function is zero at locations outside the pulse. Hence, by given the weighted function g_i in the pulse $[g_1 \ g_2 \ \dots \ g_n]$, it forms a matrix $\mathbf{H}$ when the pulse moves along the fiber, where n denotes the locations that are covered by the width of the pulse. The g_i represents the power distribution in the weight function at that location i . The Brillouin scattering power at each location can be $P_{B(1)}$ to $P_{B(N)}$ on the fiber and the measured Brillouin scattering can be $P_{MB(1)}$ to $P_{MB(N)}$ and N is the number of readings on the fiber. In the forward process, the measured Brillouin power $\mathbf{y}$ can be calculated as the product of the system weight function $\mathbf{H}$ and the real local Brillouin power $\mathbf{p}$. They are given as

$$\mathbf{y} = \mathbf{H} \cdot \mathbf{p}$$

$$\mathbf{H} = \begin{bmatrix} g_1 & g_2 & \dots & g_n & 0 & \dots & 0 & 0 & 0 & 0 \\ 0 & g_1 & g_2 & \dots & g_n & 0 & \dots & 0 & 0 & 0 \\ 0 & 0 & g_1 & g_2 & \dots & g_n & 0 & \dots & 0 & 0 \\ 0 & 0 & 0 & g_1 & g_2 & \dots & g_n & 0 & \dots & 0 \\ & & & & & \vdots & & & & \\ 0 & 0 & 0 & 0 & 0 & \dots & g_1 & g_2 & \dots & g_n \end{bmatrix}$$

$$\mathbf{y} = \begin{bmatrix} P_{MB(1)} \\ P_{MB(2)} \\ \vdots \\ P_{MB(N-n)} \end{bmatrix} \quad \mathbf{p} = \begin{bmatrix} P_{B(1)} \\ P_{B(2)} \\ \vdots \\ P_{B(N)} \end{bmatrix} \quad (6)$$

In the back-analysis process, we need to solve $\mathbf{p}$ with known $\mathbf{H}$ and $\mathbf{y}$. Due to $\mathbf{H}$ being singular, we regularize the problem. A common approach to solve this problem is to minimize the weighted sum of the 'energy' of vector $\mathbf{p}$ as well as the energy of the error (Tikhonov regularization) [15]:

$$\min\{\|\mathbf{H}\mathbf{p} - \mathbf{y}\|_2^2 + \lambda\|\mathbf{p}\|_2^2\} \quad (7)$$

Taking the derivative of this objective function, we get

$$\frac{\partial}{\partial \mathbf{p}} J(\mathbf{p}) = 2\mathbf{H}^T(\mathbf{H}\mathbf{p} - \mathbf{y}) + 2\lambda\mathbf{p} \quad (8)$$

Setting the derivative to zero,

$$\frac{\partial}{\partial \mathbf{p}} J(\mathbf{p}) = 0 \Rightarrow \mathbf{H}^T\mathbf{H}\mathbf{p} + \lambda\mathbf{p} = \mathbf{H}^T\mathbf{y} \quad (9)$$

$$\Rightarrow (\mathbf{H}^T\mathbf{H} + \lambda\mathbf{I})\mathbf{p} = \mathbf{H}^T\mathbf{y} \quad (10)$$

The solution can be derived as

$$\mathbf{p} = (\mathbf{H}^T\mathbf{H} + \lambda\mathbf{I})^{-1}\mathbf{H}^T\mathbf{y} \quad (11)$$

where $\mathbf{I}$ is the identity matrix, λ is a parameter that depends on the noise level of $\mathbf{H}$. In this least square function Eq. (7), minimizing $\|\mathbf{H}\mathbf{p} - \mathbf{y}\|_2^2$ forces $\mathbf{p}$ to be consistent with the output $\mathbf{y}$ and minimizing $\|\mathbf{p}\|_2^2$ forces $\mathbf{p}$ to have low energy. To improve the simulation result in the presence of regression noise, we minimize the energy of the derivative of $\mathbf{p}$ instead. Minimizing the summation of the two terms in Eq (7) forces $\mathbf{p}$ to be consistent with $\mathbf{y}$ and forces $\mathbf{p}$ to be smooth at the same time. For noisy data $\mathbf{y}$, a larger λ is needed to attenuate the noise.

But if λ is too large, then the estimate of the input signal is distorted. To achieve the best simulation result, λ needs to be optimized. By changing the identity matrix $\mathbf{I}$ to the derivative matrix $\mathbf{D}$, the following new solution is derived.

$$\mathbf{p} = (\mathbf{H}^T \mathbf{H} + \lambda \mathbf{D}^T \mathbf{D})^{-1} \mathbf{H}^T \mathbf{y} \quad (12)$$

$$\mathbf{D} = [1 \quad -1]$$

B. Data reliability

As shown in Fig.4, the systematic measurement error of Brillouin based strain measurement at each location is linearly proportional to the measured strain gradient at that location. This causes differences in data reliability among the data points obtained from the same optical fiber.; that is, the data reliability depends on the gradient of the distributed strain profile. Therefore, it is not appropriate to treat all data points equally in the inverse analysis.

Herein, the data reliability index DRI ($\mathbf{W}$) is introduced by defining the different reliability level at each data point. The objective function is then changed to

$$\min \left\{ \left\| \mathbf{W}^{\frac{1}{2}} (\mathbf{H}\mathbf{p} - \mathbf{y}) \right\|_2^2 + \lambda \|\mathbf{A}\mathbf{p}\|_2^2 \right\} \quad (13)$$

where $\mathbf{W}$ is the matrix that quantifies data reliability and $\mathbf{A} = \mathbf{D} \times \mathbf{W}$.

Taking the derivative of this objective function, we get

$$\frac{\partial}{\partial \mathbf{p}} J(\mathbf{p}) = 2\mathbf{H}^T (\mathbf{W}\mathbf{H}\mathbf{p} - \mathbf{W}\mathbf{y}) + 2\lambda \mathbf{A}^T \mathbf{A}\mathbf{p} \quad (14)$$

Setting the derivative to zero,

$$\frac{\partial}{\partial \mathbf{p}} J(\mathbf{p}) = 0 \Rightarrow \mathbf{H}^T \mathbf{W}\mathbf{H}\mathbf{p} + \lambda \mathbf{A}^T \mathbf{A}\mathbf{p} = \mathbf{H}^T \mathbf{W}\mathbf{y} \quad (15)$$

$$\Rightarrow (\mathbf{H}^T \mathbf{W}\mathbf{H} + \lambda \mathbf{A}^T \mathbf{A})\mathbf{p} = \mathbf{H}^T \mathbf{W}\mathbf{y} \quad (16)$$

The solution is given by

$$\mathbf{p} = (\mathbf{H}^T \mathbf{W}\mathbf{H} + \lambda \mathbf{A}^T \mathbf{A})^{-1} \mathbf{H}^T \mathbf{W}\mathbf{y} \quad (17)$$

Since data reliability is linearly related to strain gradient, the data reliability index can be calculated by strain gradient σ'_i :

$$\mathbf{W} = \max(\sigma'_i) - \left\| \frac{\sigma'_i - \text{mean}(\sigma'_i)}{\text{std}(\sigma'_i)} \right\| \quad (18)$$

Figure 4 Profile of a step strain followed by a polynomial strain change shape and the normalized data reliability index (DRI ($\mathbf{W}$)).

For example, assume that we have a true strain profile which is a simple rectangular strain in addition to a polynomial strain

profile, both with maximum 2000 $\mu\epsilon$, as shown in Fig. 4. The rectangular strain is applied from 1.5 m to 3 m and the polynomial strain is applied from 4 m to 5 m. The data reliability index DRI ($\mathbf{W}$) distribution of this profile is also shown in the figure. The sections with large strain gradient values have low weights during the back-analysis process because the $\mathbf{W}$ of these data points indicate low data reliability values. The $\mathbf{W}$ values of the polynomial section are relatively larger than those of the step change sections.

The strain profile shown in Fig. 4 is simulated and back analyzed with and without considering the data reliability to demonstrate the effectiveness of introducing $\mathbf{W}$. The simulated input and the reconstructed strain are shown in Fig 5. When data reliability is ignored, the $\mathbf{W}$ is assumed to be 1 for all data. In this figure, the reconstructed strain that incorporates data reliability shows better agreement with the input strain than that without considering data reliability.

Figure 5 Illustration of the simulated reconstructed strain using the data interpretation algorithm a) with considering data reliability and b) without considering data reliability.

The accuracy of the two data interpretation methods (with or without considering $\mathbf{W}$) is evaluated quantitatively by the standard deviation error R , which is defined as

$$R = \sqrt{\frac{1}{N} \sum_{i=1}^N (\varepsilon_i^x - \varepsilon_i^y)^2} \quad (19)$$

where ε_i^x is the reconstructed strain and ε_i^y is the true strain level. The number of measurement point is N . The calculated R value of the reconstructed strain using the new algorithm with considering data reliability is 42.5 $\mu\epsilon$, whereas that without considering data reliability is 122.9 $\mu\epsilon$. Hence, the accuracy is improved for more than 65.4% by introducing the proposed data reliability analysis, especially for the polynomial strain section.

C. Algorithm characterization

The peaks in the Brillouin spectrum could be buried in the noise level when strain change occurs in short length (such as cracks). In this section, the maximum accuracy that the proposed algorithm can achieve after considering the noise of the sensing system is simulated.

Fig. 6 and Fig. 7 shows the error values for the different strain scenarios considered in this study. Fig. 6 shows the simulated

back analyzed error before and after applying this algorithm as a function of strain section length and strain magnitude on the strain change. Different step strain change cases with varying strain lengths (0.1, 0.2, 0.3, 0.4, 0.5, 0.6 and 1.0 m) and magnitudes (100, 500, 1000 and 3000 $\mu\epsilon$) of a rectangular strain profile shown in Fig. 4 are simulated. White noise (about 15 $\mu\epsilon$ which is specified by the interrogator's datasheet) is added to the simulated Brillouin scattering spectrum of each strain scenario before the back-analysis process is considered. The standard deviation error R (given in Eq. 19) of the reconstruct strain with or without the back-analysis method for different sets of strain section length and strain are shown in Fig. 6. When the strain length is less than 0.4 m, the error increases with a decrease in strain section length because of the spatial resolution of the interrogator (1 m in this case). When strain section length is greater than 0.4m, the error becomes independent of strain section length. The error is affected by the signal to noise ratio, Brillouin spectrum linewidth of the sensing system and white noise [16].

The back-analysis reduces the error when the strain level is large. For example, when a strain level of between 500 and 3000 $\mu\epsilon$ is applied to a strain section length of 0.4m, the error is reduced from hundreds of $\mu\epsilon$ to about 50 $\mu\epsilon$. However, when the strain level is 100 $\mu\epsilon$, the back-analysis does not effectively reduce the error and the error remains to be about 20 $\mu\epsilon$ even the back-analysis is applied. This is because the spatial resolution related spectrum deformation induced error is small when strain change is small.

Figure 6 The simulated back-analyzed error of after applying data interpretation algorithm as a function of strain section length with step strain as 100 $\mu\epsilon$, 500 $\mu\epsilon$, 1000 $\mu\epsilon$, 2000 $\mu\epsilon$, and 3000 $\mu\epsilon$.

To evaluate the algorithm when the sensing fiber is long and the signal to noise ratio reduces due to the long sensing distance, Fig.7 is plotted to show the performance of the algorithm at different sensing distances. The strain is set to be 100 $\mu\epsilon$ or 3000 $\mu\epsilon$ and the strain section length is 0.4m. The sensing distances examined are 500m, 8km, 12km, 17km and 20km. The power loss on the fiber is assumed to be 0.3dB/km. The error is simulated by the model developed by Mei et al. 2019 [16]. The result shows that the algorithm can reduce the error to a certain level, which is dominated by system noise, and it works better at a short fiber length. When fiber length increases

or SNR reduces, the error after back-analysis increases. The major reason is, when SNR is low, the system noise induce error becomes much more significant than the spatial resolution related-spectrum deformation error so that the algorithm cannot fully recover the errors.

Figure 7 The simulated back-analyzed error of after applying data interpretation algorithm for detecting a 3000 $\mu\epsilon$ and 0.4m strain section length at the end of 500m, 8km, 12km, 17km and 20km optical fiber. The power loss on the fiber is set to be 0.3dB/km.

V. TEST CASE

The effectiveness of the proposed strain reconstruction algorithm is verified by conducting a step strain change experiment in the laboratory.

A. Tension test

The geometrical configuration of an optical fiber tested in the experiment is shown in Fig. 8. The cable (Fujikura reinforced strain sensing cable), which has a modulus of elasticity as 70 GPa, was hung vertically and clamped at three points. Weight 1 (3.5 kg) and weight 2 (8.5 kg) were applied at clamp 2 and clamp 3 locations, respectively, to extend the cable in two sections. In section 1, the sensing cable was extended by both weight 1 and weight 2, while in section 2 the sensing cable was extended by only weight 2. As a result, the input step strain at section 1 was always greater than that at section 2.

Figure 8 Graphical illustration of the test set up

Section 1 had a length of 0.65m (shorter than interrogator's spatial resolution), whereas section 2 had a length of 1.05 m (longer than interrogator's spatial resolution). The tested strain should be $1750 \mu\epsilon$ at section 1 and $1250 \mu\epsilon$ at section 2. The interrogator was connected close to section 2 (see Fig. 8), and therefore the measured strain profile shows the low strain section (section 2) first and then the high strain section (section 1). The raw Brillouin scattering measured profile (shown in Fig. 9) and the 3D Brillouin scattering spectrum power at each location along the fiber (shown in Fig. 10) were measured by Neubrescope NBX-5000 interrogator which was connected to the end of Section 2.

B. Spectrum decomposition

The back-analysis process was conducted based on the measured strain gradient information. The raw Brillouin spectrum was decomposed based on the proposed algorithm. The determined weights, which are derived from measured strain gradient, are plotted in Fig. 9. Low weights are assigned by the algorithm at data points near strain transition sections where the strain gradients are large.

Figure 9 Measured strain profile and its data reliability index profile.

Fig. 10 and Fig. 11 illustrate the measured 3D Brillouin spectrum and the back analyzed 3D Brillouin spectrum using the proposed data interpretation algorithm with the weight index values shown in Fig. 9. It can be clearly seen that the gradually strain change shown in Fig. 10 due to interrogator spatial resolution limit is reconstructed back to a sharp strain change profile as shown in Fig. 11.

Figure 10 Interrogator measured Brillouin scattering spectrum power

Figure 11 Back analyzed Brillouin scattering spectrum power

To show the spectrum decomposition process more clearly, Fig. 12 presents the measured spectrum at a strain transition point from a non-strain section to Section 2, which is at clamp 3 (at 4.5m in Fig. 10 and Fig. 11), and its decomposed spectrum using the proposed algorithm. The composed spectrum bandwidth is the same as the spectrum bandwidth where uniform strain is applied in the spatial resolution. The measured spectrum has a larger bandwidth and a higher peak value due to pulse convolution. The weight index is used to calculate the power contribution of the two decomposed spectrums. The back analyzed spectrum successfully separates the two Brillouin spectrum profiles from the composed spectrum, representing measurements at both strain and non-strain sections.

Figure 12 The interrogator measured Brillouin spectrum and back analyzed decomposed spectrum.

C. Results and discussion

After fitting the decomposed spectrum and detecting the peak center frequency, the strain profile estimated using the proposed algorithm is illustrated in Fig. 13. The red points are the interrogator measured distributed strain data, the black points are the true strain values and the blue points are the back analyzed strains. The error (the average difference between the input and back analyzed strain) of the strains derived using the back-analysis algorithm is $104 \mu\epsilon$, whereas the error directly measured from the interrogator is $401 \mu\epsilon$, which is close to 4 times higher than the error after using the algorithm.

The result of this verification exercise demonstrates that highly accurate shape reconstruction is possible by decomposing the measured Brillouin power at each frequency

as well as taking advantage of the measured strain gradient data from the interrogator. This procedure, which introduces spectrum decomposing using a weight function with data reliability factor, can be a general way of reconstructing strain information for distributed fiber optics sensor.

Figure 13 Reconstructed strain using the back-analysis method with a connected step shape input strain

VI. CONCLUSION

In this work, we proposed a strain data interpretation algorithm through (i) decomposing Brillouin power spectrum along the cable length with a characterized weight function and (ii) considering the reliability of the data point measurements that is evaluated from the measured strain gradient information. The algorithm is based on minimizing a weighted sum of regularization objective function so that the inverse problem of the measured Brillouin spectrum data can be solved. It uses a weight function that suits for different strain levels and minimizes the effect of low-qualified power data on strain profile during reconstruction. The algorithm obtains the peak frequency of the Brillouin spectrum by statistically analyzing the weighted power data using the least square method. The advantage of this algorithm is that the deformed strain profile can be corrected back toward the true strain profile in most cases. Further work is currently conducted to apply this data correction approach at actual site measurements which have more complex strain distribution profiles.

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