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Brillouin distributed strain sensor performance improvement using FourWaRD algorithm

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ABSTRACT

This paper presents an improvement of dynamic range as well as the strain resolution of the proposed 70 km Brillouin distributed sensor using Fourier wavelet regularised deconvolution (FourWaRD) algorithm. We have investigated the deconvolution algorithms such as: Fourier deconvolution (FourD), Fourier regularised deconvolution (FourRD) and (FourWaRD) in this paper. The Landau–Placzek ratio (LPR) is used for extracting the strain profile of the proposed sensing system with the interrogating technique based on optical time domain reflectometry (OTDR). Numerical simulation result shows that the strain resolution is enhanced about eighteen times at 70 km distance using FourWaRD algorithm compared to FourD algorithm. Similarly, the dynamic range of 49.1 dB is achieved using FourWaRD algorithm whereas 32.77 dB and 45 dB are observed using FourD and FourRD algorithms respectively. The proposed system exhibits a spatial resolution of 10 m using 10 mW launched power for 70 km sensing range.

1. Introduction

Fibre sensors are developed for numerous applications in civil, medical and military applications [1] in past three decades. These sensors are also used in oil and gas industries as well as have been extensively used to monitor environmental parameters such as position, strain, temperature, humidity etc. The reliability of conventional electrical sensors decreases under harsh environment and also creates the possibility of an explosion inside the oil or gas wells. But fibre sensors offer high reliability for in-well applications due to their passive in nature. Nowadays, most of the commercially available fibre sensors are intrinsic in nature. Recently, distributed fibre sensors are an attracting option for structural and environmental health monitoring applications, because of their unique and real time based sensing mechanism for long range applications [2,3]. The most common scattering mechanisms such as Raman and Brillouin are widely used for distributed sensing. Raman scattering approaches for temperature sensing are very popular and commercialised because it possess a very good temperature accuracy. However, it is insensitive to strain whereas Brillouin scattering effect is dependent on both temperature and strain. The frequency shift of the Stokes Brillouin backscattered light called Brillouin frequency shift varies greatly with tensile strain was observed by Horiguchi et al. [4]. Brillouin scattering based sensors can be realised using spontaneous Brillouin scattering effect as well as stimulated scattering effect. The stimulated Brillouin scattering based measurement requires to access both ends of the fibre and it has more complex receiver scheme. However, it measures accurate temperature and strain resolution. On the other hand, the spontaneous Brillouin scattering based distributed fibre sensor requires to access only one end of the fibre and it has simpler receiver scheme. These sensors can be implemented using time domain techniques such as Brillouin Optical Time Domain Reflectometer (BOTDR) [5] and Brillouin Optical Time Domain Analysis (BOTDA) [6]. We have considered OTDR technique and spontaneous Brillouin scattering for strain sensing of the proposed intensity based sensor. We have extracted the strain information from the proposed sensor using LPR and the deconvolution algorithms for 70 km of sensing range. The proposed sensor will best suitable for health monitoring applications of engineering structures of importance.

2. Mathematical model

In this paper, we have proposed a Brillouin distributed strain sensor using LPR and deconvolution algorithms. The strain profile extracted from the proposed sensor using LPR over 70 km sensing range. The principle of OTDR is used to extract the strain profile of the proposed sensing system. The schematic of the proposed strain sensor is given in Fig. 1.

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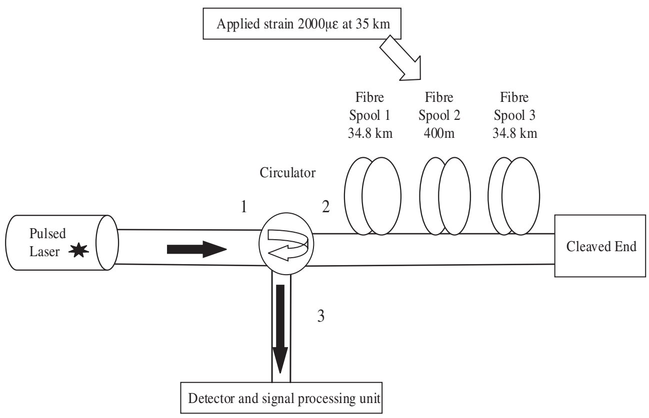

Fig. 1. Schematic of proposed sensing system.

In the proposed sensor, we have measured the Brillouin backscattered signal intensity at the input fibre end to extract the strain profile. The Brillouin backscattered impulse response $f(t)$ which is defined as the backscattered signal power in response to an injected unit delta function signal is used to calculate backscattered power. Considering constant propagation loss of fibre throughout its length, $f(t)$ is expressed as

$$f(t) = \frac{1}{2}\alpha_B v_g S p_{\text{in}} \exp(-2\alpha z) \quad (1)$$

where v_g is the group velocity within the fibre defined as c/n, S is the backward capture coefficient, P_{in} is the optical power injected to the fibre, c is the light velocity in vacuum, n is the refractive index of silica and α_B is the Brillouin scattering coefficient of the fibre defined as [7]

$$\alpha_B = \frac{8\pi^3 n^8 p^2 k_B T}{3\lambda_0^4 \rho v_\alpha^2} \quad (2)$$

In the above expression, n is the refractive index, p is the photoelastic coefficient, k is the Boltzmann constant, T is the ambient temperature of the fibre, ρ is the density of the silica, v_a is the acoustic velocity and λ_0 is the wavelength of the incident light. The received backscattered power at the input end of the fibre $P(t)$ can be expressed as the convolution of the injected pulsed power $p(t)$ and the backscatter impulse response $f(t)$ and is given by

$$P(t) = p(t) \otimes f(t) \quad (3)$$

In numerical simulation process, we have considered a pulse of width w_0, and power p_{in} is launched in to the sensing fibre and have received the Brillouin backscattered power at the input fibre end with the addition of white Gaussian noise. In order to calculate LPR, which is the ratio of Rayleigh intensity to Brillouin intensity we have calculated Rayleigh backscattered power P_R, with the function of fibre length z is expressed as [8]

$$P_R(z) = \frac{1}{2} p_{\text{in}} \gamma_R w_0 S v_g \exp(-2\gamma_R z) \quad (4)$$

where γ_R is the Rayleigh scattering coefficient. The strain dependence of the Brillouin backscattered signal intensity is given by [9]

$$I_B = \frac{I_R T}{T_f \left(\rho v_\alpha^2 \beta_T - 1\right)} \quad (5)$$

where I_R and I_B are the Rayleigh and Brillouin backscattered signal intensities respectively, T_f is the fictive temperature, v_a is the acoustic velocity, ρ is the density of silica, β_T is the isothermal compressibility, T is the ambient temperature and the acoustic velocity v_a can be expressed as [9]

$$v_a = \sqrt{\frac{E(1-\sigma)}{\rho(1+\sigma)(1-2\sigma)}} \quad (6)$$

where E is the Young's modulus and σ is the Poisson's ratio. The variation of Young's modulus of silica with the strain is given by $E = E_0(1 + 5.75\varepsilon)$ [10]. Where E_0 is Young's modulus in unstrained fibre and ε is tensile strain applied to the fibre. Assuming the Poisson's ratio is independent of strain, I_B can be rewritten as

$$I_B = \frac{k_1 I_R}{(k_2(1 + 5.75\varepsilon)) - 1} \quad (7)$$

where $k_1 = T/T_f$ and $k_2 = \left(E_{0\beta_T}(1-\sigma)\right)/((1+\sigma)(1-2\sigma))$.

In order to obtain the strain profile along the sensing fibre, the LPR at the unknown strain ε is compared with the known reference strain ε_R, and given by

$$\varepsilon = \frac{1}{K_s}\left(1 - \frac{\text{LPR}(\varepsilon)}{\text{LPR}(\varepsilon_R)}\right) + \varepsilon_R \quad (8)$$

The strain sensitivity used for simulation process of the proposed sensor K_s.

Table 1
Simulation parameters of the proposed system.

Symbols	Parameters	Values
α	Fibre attenuation coefficient	0.2 dB/km
k	Boltzmann's constant	1.38×10^{-23} J/K
S	Backward capture coefficient	1.7×10^{-3}
n	Fibre refractive index	1.45
γ_R	Rayleigh scattering coefficient	4.6×10^{-5} 1/m
p	Photo-elastic coefficient	0.286
ρ	Density of silica	2330 kg/m^3
T_f	Fictive temperature	1950 K
E_0	Young's modulus	71.7 GPa
β_T	Isothermal compressibility	7×10^{-11} m^2/N
σ	Poisson's ratio	1.16

3. Simulation and results

Using numerical simulation, Rayleigh backscattered power as well as Brillouin backscattered power are calculated with additive white Gaussian noise of variance $\sigma^2 = 10^{-7}$ W for 70 km sensing distance. We have used an optical laser source operating at 1550 nm with 10 MHz linewidth and peak power of 10 mW. A rectangular pulse of 100 ns duration used for the simulation. The other parameters used for simulation are tabulated in Table 1. The Brillouin backscattered signal is obtained using FourD, FourRD and FourWaRD algorithms.

In FourD algorithm, the Brillouin backscattered signal is deconvolved using direct deconvolution without applying any denoising technique. In FourRD algorithm, scalar shrinkage in Fourier domain is employed to estimate the Brillouin backscattered signal from the noisy signal obtained in FourD algorithm. Similarly, in FourWaRD algorithm, scalar shrinkages in the both Fourier and wavelet domains are employed to estimate the Brillouin backscattered signal from noisy signal. The regularisation of the noisy Brillouin backscattered signal has been done by using Tikhonov shrinkage parameter $\alpha = 0.00035$ [11] in both FourRD and FourWaRD algorithms. The steps involved in FourWaRD algorithm for simulation are such as:

(a) Obtain Brillouin backscattered signal using Fourier deconvolution, shrinkage with Tikhonov shrinkage parameter α and calculate inverse Fourier transform.