Abstract

Distributed optical fibre sensors, based on Brillouin scattering, have attracted interest in recent decades for use in health and safety monitoring of civil engineering structures. Brillouin Optical Time Domain Reflectometry (BOTDR) is capable of continuously measuring the longitudinal strain and temperature distribution along an optical fibre to an appropriate accuracy and stability. Signal processing is a crucial part of Brillouin based distributed optical fibre systems due to its capability to improve spatial resolution, strain and temperature resolution, and accuracy over distance. In this study, the contributions from the signal processing part of a Brillouin based distributed optical fibre sensing system are first reviewed, including both traditional frequency sweeping and digital signal processing methods. The review shows that advanced signal processing methods have the potential to improve BOTDR system performance.

As a substitution for frequency sweeping of the BOTDR system, this study uses the short time Fourier transform (STFT), which is a signal processing method used to solve a fast time-varying frequency signal. The process procedure and algorithm for this STFT-BOTDR system includes averaging, Brillouin central frequency detection, sliding window types, and lengths. In addition, zero padding, interpolation and Lorentzian curve fitting, cubic interpolation can provide both relatively low spatial resolution and strain/temperature resolution. When the sliding window function is applied to STFT, long-window offers a better frequency resolution, while short-window offers better performance for small event detection. Long and short windows can be combined to enhance the capability of small event detection while keeping the same frequency resolution, optimising the result from the analysis of multiple windows. In general, STFT-BOTDR can obtain high speed distributed temperature and strain measurements with high readout resolution, temperature and strain resolution, and spatial resolution. It can also be used to detect events at less than the spatial resolution, such as cracks.

In BOTDR, the distributed strain and temperature are obtained by detecting the peak power frequency of each Brillouin gain spectrum along the optical fibre. Therefore, study into the shape of the Brillouin gain spectrum is important. In this study, a step-shape temperature

distribution is proposed to analyse the Brillouin gain spectrum caused by the non-uniformly distributed temperature. The Brillouin gain spectrum distortion includes double peaks and single peaks, which are controlled by the Brillouin frequency shift separation and the individual power. These spectrum deformations introduce distance error to the step-shape temperature distribution. The measured transition position of the events is shifted due to the Brillouin gain variance in the two events, which can be recovered by applying the measured peak powers of the Brillouin gain spectrum to a calculation to compensate for the position error.

In this study, the frequency resolution, corresponding strain and temperature resolution of the Brillouin distributed optical fibre sensors are studied using a Monte Carlo simulation by determining the statistical variance of the peak power frequency of a Lorentzian-shaped Brillouin gain spectrum when a random noise signal is applied to the amplitude. By varying the SNR, Q factor and frequency step, the minimum detectable change of the Brillouin signal is obtained by direct detection and fitting. The results show that a Brillouin gain spectrum with a high Q-factor, a high SNR and a densely sampled spectrum can produce a low minimum detectable change. Allan variance is the most common time domain measure for frequency stability and this study demonstrates that Allan variance can be used to estimate the noise source in a BOTDR system, and to determine the optimal averaging time.

Two signal processing approaches (bilinear time-frequency transforms and Kalman filters) are introduced to improve the performance of distributed strain and temperature measurement. Five bilinear time-frequency transforms are used to generate the 3D Brillouin spectrum along the fibre under test conditions, and the corresponding distributed Brillouin central frequency is measured. The results show that Smoothed Pseudo Wigner-Ville can offer good spatial resolution and frequency resolution at the same time. Bilinear time-frequency transforms can produce higher spatial resolution and higher frequency resolution than a linear time-frequency transform (i.e. STFT) for a BOTDR system. A Kalman filter can also be applied to the distributed Brillouin central frequency profile in order to improve the frequency resolution. The results show that a Kalman filter can be used to improve the frequency resolution when the averaging time is restricted.