Distributed sensing: from Rayleigh to Brillouin scattering

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Abstract

Distributed sensors provide the tempertaure, strain, vibration and acoutsic wave measurement at centimeters resolution over kilometer length. They are the ideal tools for the safety and security monitoring of large civil structures.

Introduction

In recent years, structural health monitoring (SHM) has become a new field in civil, mechanical and aerospace engineering and sensor instrumentation. The applications of SHM include large infrastructures (e.g. bridges, dams, buildings, and tunnels), oil and gas pipelines, vehicles (such as aircraft, ships and cars), and biomedical devices. Many public civil structures are facing the age problems. It has been reported that 40% of the bridges in Canada are 50 years old [1], while the number in United States is over 50% and 42% of all bridges are structurally deficient [2] . Then it is crucial to determine when the structure needs to be repaired or reinforced to eliminate the risk of catastrophic structural failure. Manual inspections currently can not be conducted very often due to their costs, and accordingly the early signs of potential problems could be lost. As a result, a real-time automated monitoring system becomes extremely in demand for detecting failures in early stages. Accordingly, there is a clear need for a technique that is able to provide a continuous reading of the measurand as a function of position along the sensing fiber to cover large civil structures for the conditional monitoring.

Using standard communictaion fiber, one can make intrusion [3] and vibration sensing [4] based on Rayleigh scattering OTDR (optcial time domain reflectrometer) [5]; temperature and strain sensing based on B-OTDR and B-OTDA (optical time domain analysis) [6-8]. The strain and tempertaure sensors have been used to measure the strains in steel [9], and concrete structures [10]. The distributed sensor can provide information with centimeter spatial resolution in kilometer long fiber for strain and tempertaure monitoring which is crucial for the structural monitoring [11].

The mechanisms of distributed sensors are based on backscattered light inside the optical fiber including Rayleigh, Brillouin and Raman scattering as shown in Fig.1. The centre line is called Rayleigh scattering. It results from nonpropagating density fluctuations, which in turn causes random microscopic variations in the refractive index. Rayleigh scattering is an elastic scattering process, i.e. the frequencies of incident and scattered light are equal. The two spectral lines caused by Brillouin scattering appear on both sides of the Rayleigh peak. By definition, the line with frequency downshift is known as Stokes component, whereas the line with frequency upshift is known as anti-Stokes component. Brillouin scattering is attributed to sound waves, which are propagating pressure waves and hence refractive index waves in the medium. Raman scattering results from the interaction of light with molecular vibrations in the medium, or also known as optical phonons.

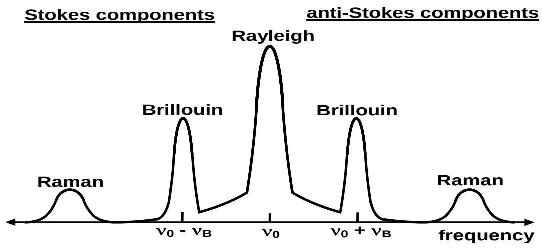


Fig. 1: Spontaneous scattering components.

Rayleigh OTDR for dynamic monitoring

The simplest distributed sensor is based on Rayleigh scattering and is widely used in optical communication for its loss measurement along the fiber length. The pulse width equivalent length is the spatial resolution.

Up to now, the distributed optical fiber sensors have been mainly used for quasi-static measurements, i.e. no time-varying or slowly time-varying signals, such as, static strain or temperature in seconds to minutes time scale. Dynamic measurements (ms to micor second) using the above techniques are difficult to achieve because of the large number of waveforms average to remove the polarization effect induced signal fluctuation or because of the large range of frequency scans that are needed in order to obtain a reasonable signal to noise ratio (SNR) for the distributed Brillouin sensors.

Recently a truly distributed vibration sensor has been demonstrated based on the spectrum density of Polarization-OTDR system. [4]. This new sensor can detect the vibration frequency of 5 KHz over 1km sensing length with 10m spatial resolution.

In conventional POTDR, the SOP is measured with 4 polarization controllers so that the rotation angle of SOP can be measured in every location to recover the PMD or strain, this process takes minutes, as a result, it can only be used for static measurement. To realize dynamic measurement with ms time resolution, only one analyzer is used to identify dynamic events, through which the birefringence change along the fiber could be detected. Moreover, with a novel fast Fourier transform (FFT) spectrum analysis, multiple simultaneous events with different vibration frequencies or even with the same frequencies are able to be accurately located. The spectral density function of location change is equivalent to many variable narrowband filters with bandwidth of <1Hz to improve the SNR of multiple events detection, which allows the disturbance to be detected simultaneously at any location along the sensing fiber. Fig. 2 shows the distributed vibration measurement from such a sensor at 10m spatial resolution over 10m spatial resolution. Such a sensor can be used as an intrusion sensor and the structural vibration monitoring.

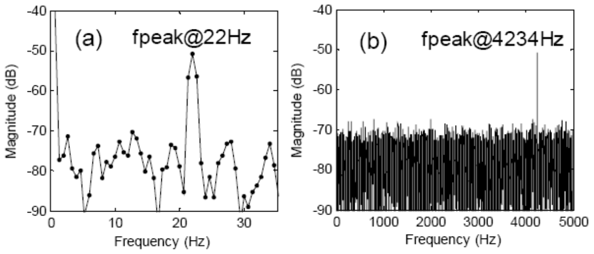


Fig. 2: Piezo fiber stretcher driven by 5Vpp square wave, FFT spectrum of time trace signal at 550m of (a) 22Hz driven signal; (b) 4234Hz driven signal

Brillouin scattering for static and dynamic monitoring

In the Brillouin sensor, the sensing mechanism takes advantage of the linear relationship between the Brillouin frequency and temperature/tensile strain variations.

Most recently a new scheme has been tested using different pulse pairs to form BOTDA [11]. Two different pulses of width τ and τ+δτ were sent as probe wave to interact with the pump wave and to generate the Brillouin loss signal. When the pump wave was scanned across the Brillouin spectrum of the fibers, the Brillouin loss spectrum at every fiber locations for two pulse widths are obtained which is then being subtracted. The difference of the Brillouin loss spectrum at each location was obtained. Because of the small pulse width difference δτ, the difference in Brillouin loss was measured, the spatial resolution is limited by the rise time of the pulse, so called different pulsewidth pair (DPP) based BOTDA . With 20 and 19 ns pulses, a 12cm spatial resolution is achieved in DPP-BOTDA by the subtraction of two BOTDA signals. The two 20cm stressed sections with 1800 and 2000με separated by a 20cm loose fiber was measured by both DPP-BOTDA with a 20/18ns pulse pair and BOTDA with a 2ns pulse. BOTDA (extinction ratio of 30dB) failed to detect the two closely located stress sections, while DPP-BOTDA was able to detect both stress sections with strain accuracy of 28με due to the narrow Brillouin spectrum of 20ns pulse in DPP-BOTDA and differential Brillouin gain detection, while BOTDA only detects one strain at the center of the two stress sections with strain resolution of over 100 με[12]. The signal to noise ratio in DPP-BOTDA can be improve by 20dB at low pump and probe power due to narrow spectral width of large pulse (20ns) and small pulse (1ns), and long inetaction length.

For distributed dyanmic strain measurement based on the birefrigence effect on the Brillouin gain, we used a 20 ns pulses equivalent to 2m spatial resolution from a light source. An 80 cm section of a 120 m fiber was bonded to a 40 cm steel cantilever which was allowed to vibrate. Figures 4(a) and (b) shows the performance of the vibration sensor in the laboratory setting (zoomed in on the fiber location which is vibrating).

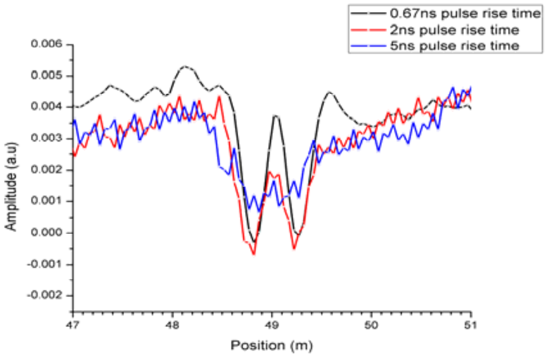
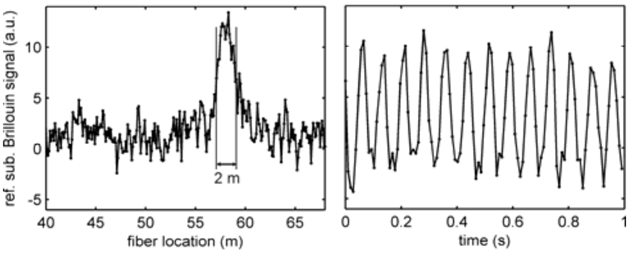


Fig. 3: Spatial resolution of DPP-BOTDA with pulse pair of 20/19ns at different pulse rise/fall time for the two stress section measurement.



(a) (b)

Fig. 4 (a) Spatial resolution of vibration sensor. (b) Vibration response of steel cantilever

Conclusions

The distributed sensors are capable for the staic and dynamic monitoring of the strain change. The spatial resolution limit of DPP-BOTDA sensor for pulse pairs with a fixed pulse width difference is determined by the rise time of the pulse while in conventional BOTDA sensor the spatial resolution, which is the pulse width equivalent fiber length, is limited by the phonon lifetime (~10ns) unless the pre-pumping scheme is applied.

References

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