OZ Optics Limited
shop.ozoptics.com
www.ozoptics.com
219 Westbrook Road
Ottawa, ON, Canada, K0A 1L0
Toll-free: 1-800-361-5415
Telephone: 1-613-831-0981
Fax: 1-613-836-5089
sales@ozoptics.com

Applications of Fiber Optic Distributed Strain and Temperature Sensors

Executive Summary

Fiber optic distributed strain and temperature sensors measure strain and temperature over very long distances and are an excellent tool for monitoring the health of large structures. These sensors leverage the huge economies of scale in optical telecommunications to provide high-resolution long-range monitoring at a cost per kilometer that cannot be matched with any other technology. Today's distributed strain and temperature sensors offer clear cost and technical advantages in applications such as pipeline monitoring, bridge monitoring, dam monitoring, power line monitoring, and border security / perimeter monitoring. Brillouin sensors are also excellent for the detection of corrosion in large structures.

Working Principle

Although a detailed understanding of Brillouin sensors is not required when using OZ Optics sensor systems in typical structural health monitoring applications, a description of the basic measurement will be useful to users who want a better understanding of the specification tradeoffs when selecting a sensor system solution.

The most common type of Brillouin strain and temperature sensor uses a phenomenon known as stimulated Brillouin scattering. The measurement is illustrated in the figure below:

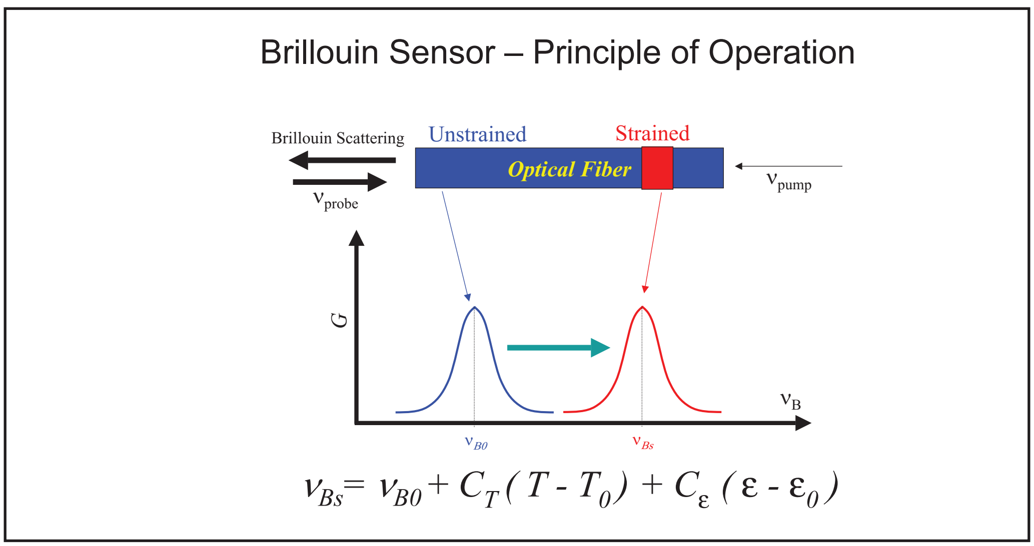

Figure 1: Brillouin spectral peaks from strained and unstrained fibers.

The typical sensor configuration requires two lasers that are directed in opposite directions through the same loop of fiber (one laser operating continuously, the other pulsed). When the frequency difference between the two lasers is equal to the "Brillouin frequency" of the fiber, there is a strong interaction between the 2 laser beams inside the optical fibers and the enhanced acoustic waves (phonons) generated in the fiber. This interaction causes a strong amplification to the Brillouin signal which can be detected and localized using an OTDR-type sampling apparatus. To make a strain or temperature measurement along the fiber, it is necessary to map out the Brillouin spectrum by scanning the frequency difference (or "beat" frequency) of the two laser sources and fitting the peak of the Brillouin spectrum to get the temperature and strain information.

As the equation at the bottom of Figure 1 shows, the Brillouin frequency at each point in the fiber is linearly related to the temperature and the strain applied to the fiber. In some optical fibers such as dispersion-shifted fiber, there are actually two peaks in the Brillouin spectrum and it is possible to extract both temperature and strain information from a single fiber. If one uses the sensor system with our patent pending sensing fiber, then one can simultaneously measure strain and temperature, while utilizing the same fiber for telecommunications.

A Comparison of Fiber Optic Sensor Technologies for Structural Monitoring

Brillouin fiber optic sensors excel at long distance and large area coverage; in fact, Brillouin sensors should be considered for any strain or temperature application with total lengths in excess of 10 meters. Another common fiber optic sensor technology appropriate for localized measurements is known as fiber Bragg grating sensors. However, for structural health monitoring, when the potential damage or leakage locations are unknown, it is difficult to pre-determine the places to put fiber Bragg grating sensors or other types of point sensors. Fiber Bragg grating sensors are an excellent localized sensor when the specific area(s) of interest are known. Distributed Brillouin sensors can be used for much broader coverage and can locate fault points not known prior to sensor installation.

There are two types of Brillouin fiber optic sensors. Brillouin Optical Time Domain Reflectometers (BOTDR) resolve the strain or temperature based Brillouin scattering of a single pulse. Brillouin Optical Time Domain Analysis (BOTDA) uses a more complicated phenomenon known as Stimulated Brillouin Scatter (SBS).

For Stokes scattering (including Brillouin scattering and Raman scattering) only a small fraction of light (approximately 1 in 10^3 photons) is scattered at optical frequencies different from, and usually lower than, the frequency of the incident photons. Based on BOTDR technology, since the intensity of a backscattered Brillouin signal is at least $1/10^3$ less than that of the incident light, the Brillouin scattering signal is very weak. Considering the attenuation of the optical fiber, for example, 0.22 dB/km, the measurement range cannot be very long and SNR is generally worse than that found with BOTDA technology. The primary advantage of BOTDR technology is that only one end of the fiber needs to be accessible.

The BOTDA technique is significantly more powerful as it uses enhanced Brillouin scattering through two counter-propagating beams. Due to the strong signal strength the strain and temperature measurements are more accurate and the measuring range is longer than that of BOTDR technology. In addition, our patented sensing method allows one to determine simultaneous strain and temperature information.

The BOTDA method requires more optical components and a 2-way optical path so the total system cost is typically higher (the sensor fiber must be looped or mirrored). However, most field units deployed today are BOTDA systems because the additional measurement accuracy more than justifies the moderate increase in system cost.

OZ Optics' Foresight™ series of DSTS are BOTDA-based sensor systems. They offer highly accurate and fast measurement of strain and temperature. Table 1 provides a comparison of common fiber optic strain and temperature sensor techniques, along with typical performance limits for each type:

	Bragg Grating*	**BOTDR**	**Foresight™ DSTS**
Strain Accuracy	± 1 µstrain	± 30 µstrain	± 2 µstrain
Spatial Resolution	0.1 m	1 m	0.1 m
Length Range	Point sensor	30 km	100 km
Acquisition Time	<1 second	3–20 minutes	As low as 1 second
Configuration	Many fibers	Single fiber	Loop or single fibers
Temperature Accuracy	± 0.4 °C	N/A	± 0.1 °C
Strain and Temperature	Multiple fibers	Multiple fibers	Single or multiple fibers
Distributed	No	Yes	Yes
*quasi-distributed with multiple fibers			

Table 1: Typical Specifications for Fiber Optic Sensors

The simultaneous measurement of strain and temperature is possible by using our patented method. Standard singlemode fiber is used in large quantities for high speed optical telecommunications networks and is inexpensive. It is important to make a decision on the fiber type and cable structure early in any structural monitoring project. Although test equipment can be changed or upgraded in the future, it is essential to install the correct fiber type if the simultaneous measurement of strain and temperature is required.

Major Applications of Fiber Optic Distributed Strain and Temperature Sensors

Fiber optic distributed strain and temperature sensors have been applied in numerous applications. As mentioned previously, Brillouin-based systems are generally unmatched in applications that require high-resolution monitoring of large structures (very long, or very large surface areas). Unlike competing sensor technologies, Brillouin systems directly leverage the economies of scale from the millions of kilometers of fiber optic telecommunications fiber installed worldwide. As Table 2 shows below, the most common applications for distributed strain and temperature sensors involves very large linear or spatial dimensions.

Application	**Strain**	**Temperature**	**References available upon request by OZ Optics collaborators**
Bridge Monitoring	■	■	■
Pipeline Monitoring	■	■	■
Process Control	■	■	■
Structural Health Monitoring (concrete & composite structures)	■		■
Security Fences	■		
Power Lines	■	■	■
Fire Detection	■	■	■
Crack Detection	■		■

Table 2. Applications of Brillouin Fiber Optic Sensors

OZ Optics is committed to delivering solutions in each of the markets listed above. If your critical monitoring application is not listed in the table, please contact us with your requirements. To get more detailed information related to your application or request a reference article, please contact OZ Optics.

The fiber optic strand provides excellent flexibility and placement over large areas and great distances. For example: a mining conveyor belt may be tens of kilometres long in order to remove excess debris. The material is of little value and detecting a seizing bearing along the length would be difficult via conventional fire detection means. As a bearing starts to seize, it will overheat prior to causing a fire. The DSTS and sensing fiber is easily installed and will readily detect this change in heat at a bearing. While the direct cost of the damage caused by the fire is minimal, the loss of revenue from shutdown of the mining operations while the conveyer belt is repaired will be extensive.

Sample Performance Table

Distributed Brillouin measurements are quantified by four variables: precision of measurement, variation of strain and temperature to be measured, spatial resolution, and length of fiber being measured. These four interact to determine the time the measurement will take. Conversely, if time is restricted, the other qualities of measurement can be determined.

The ForeSight™ Brillouin based DSTS design enables focus on the variable of most concern. For instance, concrete fracture detection may require tight spatial resolution and high precision. The result will be a known measurement time and the maximum fiber length that can be utilized.

The measurement time of the DSTS can vary from **1 second** to **10 minutes** based up the requirements dictated by the application. The sample table below reflects some common requirements: better than ± 0.5 °C and ± 10 µε precision. All table measurements were completed in less than 1 minute 40 seconds.

The table is not a restriction of what can be achieved. Variations in the four areas of concern can be accommodated. For instance, the measurement of temperature/strain for 50 km sensing fiber, 2 m spatial resolution, with an accuracy of 0.2 °C/4 µε is attainable, but will increase measuring time to 3 minutes and 45 seconds. Another comparison of the interaction of fiber length, spatial resolution, accuracy of temperature/strain, and measurement time: 100 km sensing fiber, 6 m spatial resolution can be 0.4 °C/8 µε when measuring time is 4 minutes and 38 seconds, however the same 100 km can have a precision of 0.1 °C/2 µε when spatial resolution is increased to 50 m with a measuring time of 3 minutes and 48 seconds.

	10 cm	50 cm	1 m	2 m	3 m	4 m	5 m	10 m	20 m	50 m
<=1 km	0.3 °C/6 µε	0.2 °C/4 µε								
<=2 km	0.4 °C/8 µε	0.3 °C/6 µε	0.1 °C/2 µε							
<=4 km		0.4 °C/8 µε	0.3 °C/6 µε							
<=10 km			0.3 °C/6 µε							
<=20 km			0.4 °C/8 µε	0.06 °C/1.2 µε						
<=30 km				0.2 °C/4 µε						
<=40 km				0.3 °C/6 µε	0.1 °C/2 µε	0.2 °C/4 µε				
<=50 km					0.2 °C/4 µε	0.3 °C/6 µε	0.2 °C/4 µε	0.1 °C/2 µε		
<=60 km								0.2 °C/4 µε		
<=70 km								0.3 °C/6 µε		
<=80 km									0.2 °C/4 µε	
<=90 km									0.4 °C/8 µε	
<=100 km									0.4 °C/8 µε	0.2 °C/4 µε

Table 3. Typical Measurement Accuracy as a Function of Fiber Length and Spatial Resolution (Acquisition time ≤ 100 seconds).

Fire Detection Mode:

The DSTS may be used in a fire detection and control system The use of distributed fiber optics provides for excellent flexibility to detect fires. The fiber optic strand does not pose a spark risk or explosion risk, and if properly designed, it may be placed in an area subject to ionizing radiation. The spatial resolution is dependent on the fiber length. With a 20 km fiber length, a spatial resolution of 1 m is provided. Shorter lengths can be monitored with better spatial resolution, compared to longer fibers. Similarly, longer lengths can be monitored at the expense of resolution. Refer to Table 3 for more details.

Temperature measurement performance while in Fire Detection Mode will vary from a nominal Brillouin measurement in that the goals of the measurement are based upon fast detection of a change in temperature. The overall goal of the Fire Detection Mode is to accurately detect a change in temperature associated with a pending fire or outright fire in a nominal amount of time. Therefore the performance of the DSTS in fire detection mode will meet or be better than the following table:

Start Temperature	Required Measuring Temperature By System	Oven Setting Temperature	Specified Measurement Time	Measurement Accuracy
24 °C	30 °C	30 °C	9 sec	28 - 32 °C
24 °C	40 °C	40 °C	11 sec	38 - 42 °C
24 °C	50 °C	50 °C	13 sec	48 - 52 °C
24 °C	60 °C	60 °C	14 sec	58 - 62 °C
24 °C	70 °C	70 °C	16 sec	68 - 72 °C
24 °C	80 °C	80 °C	18 sec	78 - 82 °C

Table 4. Typical Accuracy for Fire Detection Applications

The following conditions apply for the reference table to be accurate:

- Total fiber length: 60 km
- Spatial resolution: 6 m
- Baseline must be obtained at 24 °C before temperature measurements.
- Measurement time does not include sensing cable response time.
- All sensing fiber must be same type of fiber without strain effect.

Calculating the Cost Savings for Brillouin Fiber Optic Sensors

As stated previously, Brillouin fiber sensors offer high-resolution long distance coverage for structural monitoring at a cost per kilometer unmatched by any other measurement technique. This creates the opportunity to generate a rapid return on investment for Brillouin sensor-based monitoring systems used in critical structural monitoring applications. The figure below shows a simple cost savings example:

Fiber Optic Monitoring
OZ Optics Ltd. Cost Savings Calculator

System Parameters	
Pipeline Length	50 km
Cost of Failure	$750,000 cost of leak
Downtime Cost	$20,000 per hour

Comparison		**Monitoring**	No Monitoring	Comments
Probability of Failure	% / year	**0.25%**	1%	Reduced risk of failure
Downtime	hours/year	**4.8**	24	Automated preventive maintenance
Maintenance Cost	dollars/year	**$25,000**	$50,000	Automation of routine maintenance
Total Annual Savings	**$414,625**			Total Annual Savings

Table 5: Cost Savings example

Several recent pipeline shutdowns demonstrate the need for continuous online monitoring. While the calculation in Table 5 is for a mid-sized regional distribution pipeline, the economics for major pipelines are even more compelling. The shutdown cost per day can easily exceed $10 million. With long-haul Brillouin monitoring system costs of only $1 - $2 per meter, the prevention of a single shutdown greatly exceeds the installation and operating costs of a monitoring system. Other large structures such as power lines, dams, and bridges also have very high costs associated with catastrophic failure and shutdowns.

The most important factors in a typical cost savings estimate are the reduction in maintenance/inspection cost (due to automated monitoring), the reduction in downtime, and the reduction in the potential for catastrophic failure. In many instances, the downtime and failure costs are much higher than that shown in the example.

To obtain a spreadsheet version of this cost saving calculator, to request a customized version for your structural health monitoring application, or **for more information about our strain and temperature sensor system and related products, please visit www.ozoptics.com.**

Suppressed Brillouin Response Fibers

In some single mode fibers, the Brillouin effect is suppressed in order to minimize loss. Since Brillouin effects are a type of back reflection and this energy comes at a minimal dB loss per km of fiber, some manufactures have specially designed fibers with absolutely minimal losses. While the vast majority of fibers are not engineered to remove the Brillouin effect, some are not suitable for Brillouin sensing. If you are uncertain whether or not your fiber is suitable for Brillouin measurement, ask OZ Optics.

Alternately, enhanced Brillouin effect fibers are available in the market but these are not commonly used by telecommunications applications

Background Articles

Pipeline Buckling Detection:
L. Zou, X. Bao, F. Ravet, and L. Chen, "*Distributed Brillouin fiber sensor for detecting pipeline buckling in an energy pipe under internal pressure*," Applied Optics 45, 3372-3377 (2006).

Pipeline Corrosion Detection:
L. Zou, G. Ferrier, S. Afshar, Q. Yu, L. Chen, and X. Bao, "*Distributed Brillouin scattering sensor for discrimination of wall-thinning defects in steel pipe under internal pressure*," Applied Optics 43, 1583-1588 (2004).

Power Line Monitoring:
L. Zou, X. Bao, Y. Wan and L. Chen, "*Coherent probe-pump-based Brillouin sensor for centimeter-crack detection*," Optics Letters 30, 370-372 (2005).

Crack Detection:
L. Zou and Maria Q. Feng, "*Detection of micrometer crack by Brillouin-scattering-based distributed strain and temperature sensor,*" 19th International Conference on Optical Fiber Sensors, Perth (Australia, 14-18 April 2008).

Accuracy of BOTDA Technology:
L. Zou, X. Bao, S. Yang, L. Chen, and F. Ravet, *"Effect of Brillouin slow light on distributed Brillouin fiber sensors",* Optics Letters 31, 2698-2700 (2006)

Simultaneous Measurement of Strain and Temperature:
L. Zou, X. Bao, S. Afshar V., and L. Chen, *"Dependence of the Brillouin frequency shift on strain and temperature in a photonic crystal fiber",* Optics Letters 29, 1485-1487 (2004)