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PIPELINE LEAKAGE DETECTION USING FIBER-OPTIC DISTRIBUTED STRAIN AND TEMPERATURE SENSORS

WHITE PAPER

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INTRODUCTION

Pipelines constitute an efficient solution to natural oil and gas transportation which would otherwise require thousands of tanker trucks on a daily basis [1]. Due to the severity of the economic and environmental impact associated with leakages from pipelines, oil and gas industries are constantly seeking more efficient and reliable telemetry and pipeline monitoring technologies.

Many monitoring solutions have been considered over the past few decades, with underlying technologies that include electric strain gauges, microwave wireless sensors, and optical fiber Bragg gratings (FBG). Among these various solutions, optical sensing has emerged as a strong candidate due to the inherent advantages optical fibers present; their low loss, light weight, and immunity to noise and interference, to name a few. However, most of the proposed techniques, including those based on FBG, rely on discrete, limited sets of sensing elements, thereby fulfilling only partially the true needs of the oil and gas industries.

Distributed strain and temperature sensors (DSTS) use an optical sensing technology that is based on Brillouin optical time-domain reflectometry (BOTDR), or on Brillouin optical time-domain analysis (BOTDA) to perform pipeline leakage monitoring. DSTS technology uses an entire standard telecom optical fiber as the sensing element, thus achieving a true distributed sensing function. Due to the low fiber loss, the sensing range can be as high as 100 km.

Previously installed dark telecom fibers can be leveraged to perform the sensing function, thus achieving remarkable savings on the cost of installation. Even lit optical fibers that are already being used for communications and telemetry can be turned into a distributed sensing element with the proper wavelength division multiplexing setup. The proximity of the pre-installed fiber to the potential leakage locations will impact the sensitivity and the response time of the system.

This paper presents a brief description of the DSTS principle of operation, and discusses the experimental results of pipeline leakage tests that used an OZ Optics Ltd. DSTS product, and were performed under laboratory conditions over a period of one month, by Southwest Research Institute (SwRI) and funded by major oil companies through a joint industry program.

PRINCIPLE OF OPERATION

BRILLOUIN SCATTERING

Brillouin scattering stems from the density variations that dielectric materials exhibit in the presence of an electric field[1]. If an optical signal, called a probe, is injected into one end of an optical fiber, and a strong optical signal, called a pump, is injected into the other end, then the density variations induced by the electric field of the pump will result in a distributed refractive index grating inside the fiber. The distributed grating will, in turn, cause the probe to scatter in the backward direction, as shown in Figure 1.

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[1] This phenomenon is called electrostriction.

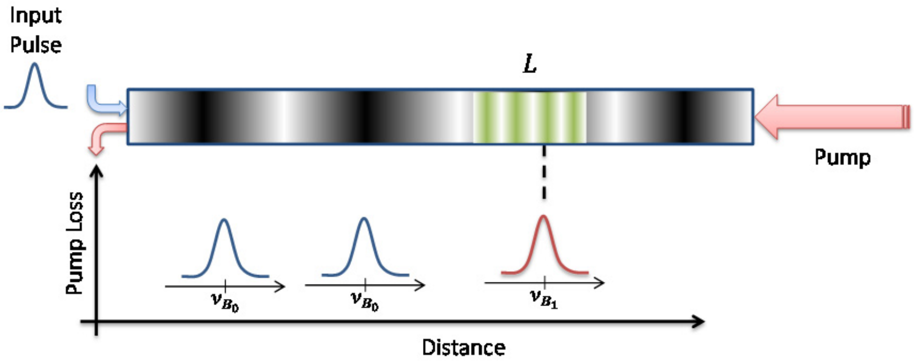

Figure 1. Brillouin scattering sensing principle.

The scattered signal is shifted in frequency by an amount ν_{B_0} called the Brillouin frequency shift. For standard single-mode fibers, operated at a wavelength of 1.55 µm, the Brillouin frequency shift is approximately $\nu_{B_0} \approx 11$ GHz. If a section of the optical fiber is stressed either mechanically or thermally, the Brillouin frequency shift of the scattered light from that fiber section, noted as ν_{B_1}, will be different from the Brillouin frequency shift of the unstressed fiber. The amount of change in the Brillouin frequency shift is proportional to the change in temperature and/or strain. This linear dependency is typically written as [2]-[4]:

$$\Delta\nu_B = \nu_{B_1} - \nu_{B_0} = C_t(T - T_0) + C_\epsilon(\epsilon - \epsilon_0)$$

where C_t and C_ϵ are the optical fiber temperature and strain coefficients, respectively. Because of the interaction between the pump and probe signal the same frequency shift can be observed in the pump, albeit in the form of loss spectrum.

BRILLOUIN OPTICAL TIME-DOMAIN ANALYSIS (BOTDA)

The BOTDA system, whose block diagram is shown in Figure 2, is based on the interaction through Brillouin scattering of a pulsed laser, acting as a probe, with a counter-propagating continuous-wave (CW) pump laser. The probe beam exhibits Brillouin amplification at the expense of the CW beam. The resultant power drop in the CW beam is measured while the frequency difference between two lasers is scanned, giving the Brillouin loss spectrum of the sensing fiber. The shift in the Brillouin spectrum of the fiber is used to calculate the temperature and/or strain change of the sensing fiber.

If the measured Brillouin frequency shift is due to a change in temperature only, then the following relationship holds: $\Delta T = \Delta\nu_B / C_t$. Therefore, a properly calibrated system with a known thermal coefficient C_t allows the translation of a Brillouin frequency shift into a temperature change. The BOTDA system has many features allowing it to achieve spatial resolutions as small as 10 cm, and to cover sensing lengths as large as 100 km. In addition, it can achieve high temperature and strain measurement accuracies of ± 0.1°C and $\pm 2\ \mu\epsilon$, respectively.

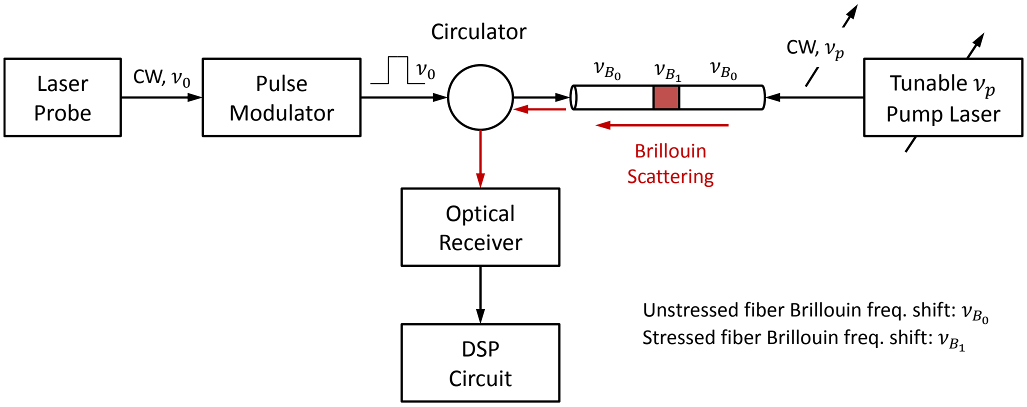

Figure 2. BOTDA block diagram.

EXPERIMENTAL PROCEDURE

The overall goal of the experimental procedure is to assess the leakage detection capabilities of the sensing technology. For that, a blind test methodology was followed in which the number and the position of the leakages were not known beforehand to the user. A description of the pipeline leakage simulation setup and the OZ Optics Ltd. BOTDA system used in the test is provided below.

PIPELINE SETUP

Figure 3 shows an example of the pipeline setup used in the tests. Within the pipeline, a system of tubing and valves was used to route the test fluid to the appropriate locations to simulate leaks.

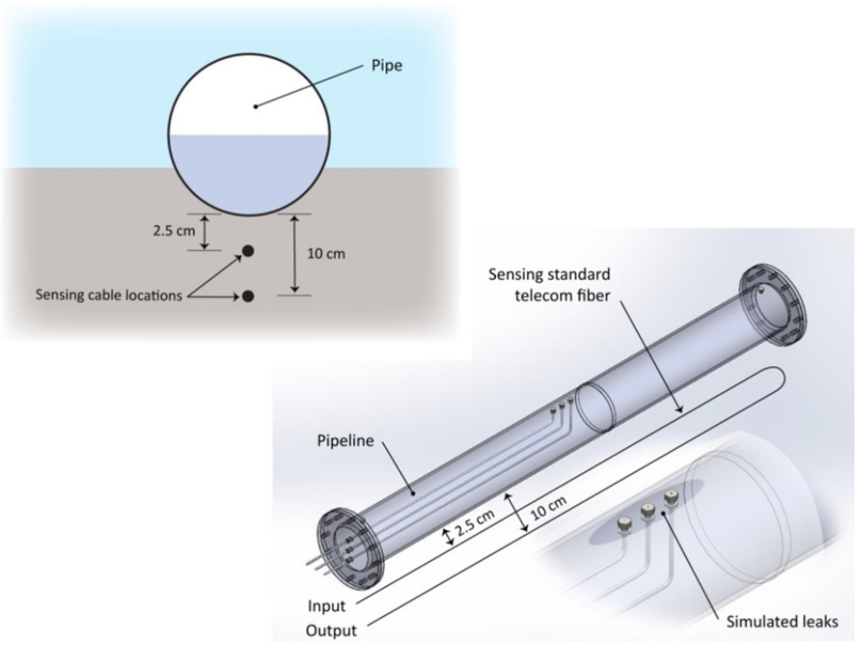

Figure 3. Example configuration of a pipeline with DSTS.

The tubing penetrated the pipe wall and a 1/8” orifice at the end of the tubing was perforated to simulate a hole in a pipeline. The orifice discharge was flush with the outside diameter of the pipe. Three orifices could be opened individually to simulate single-hole or multi-hole leakages. The remainder of the pipe was hollow and filled with water.

DISTRIBUTED TEMPERATURE SENSOR SETUP

In the experimental setup, a BOTDA system was used with a 10.3 km-long optical sensing fiber loosely placed inside a metallic cable with several buffer layers. The cable was placed in two positions, 2.5 cm and 10 cm, below the pipeline, to measure the temperature change before and after the occurrence of leakages. The CW laser operated with an output power of 300 μW at a wavelength of 1552 nm. In this setup, the measurement accuracy of the temperature was 0.15°C. The spatial information was determined by the time-domain analysis of the CW signal. A pulse width of 15 ns was used in the measurements to achieve a 1.5 m spatial resolution. The Brillouin spectrum measurements were acquired every 4 minutes, at a sampling rate of 250 MS/s, and the acquired data was averaged to decrease measurement noise.

RESULTS

A baseline measurement was performed before the occurrence of the leakages. This baseline serves as a reference to which all subsequent measurements will be compared. For instance, if the baseline is taken on the sensing fiber when its temperature is 80°F, then the measurements taken when the leakage occurs will indicate the difference in temperature from that baseline value. Figure 4 shows the results recorded by the BOTDA system when a large leakage with a 400 psi injection pressure occurred. It clearly shows that two leakages (two peaks) occurred around 10,117 m and 10,167 m. Since the system was used in a continuous monitoring mode, the figure also shows snapshots of the measurements taken as the sensing fiber was cooling down (reduced-size peaks) and approaching thermal equilibrium with its surrounding.

The BOTDA system was also capable of detecting small injection pressure leakages. Figure 5 shows the results of leakage detection with 50 psi injection pressure, with an equally accurate measurement of the leakages locations. The system initial response time to detect these events was below 2 minutes. Subsequent measurements were used to improve the reading accuracy.

CONCLUSION

DSTS technology has proven to be an efficient and cost-effective solution to pipeline leakage monitoring for oil and gas industries. It uses standard telecom fibers as the sensing element, thus allowing pipeline companies to use the technology with minimal cost of installation by leveraging already-installed, dark or lit optical fibers for leakage detection purposes. In a blind test conducted by an independent consultant, the fiber-optic based DSTS from OZ Optics Ltd. was able to detect all leakage incidents, with 40 different leakage volumes during one month of testing. Leakages from a 1/8” orifice with an injection pressure as low as 22 psi, and a temperature difference of 20°F between the soil and line temperatures, have been easily detected and accurately located. An impressive leakage detection response time of less than 2 minutes has been achieved.

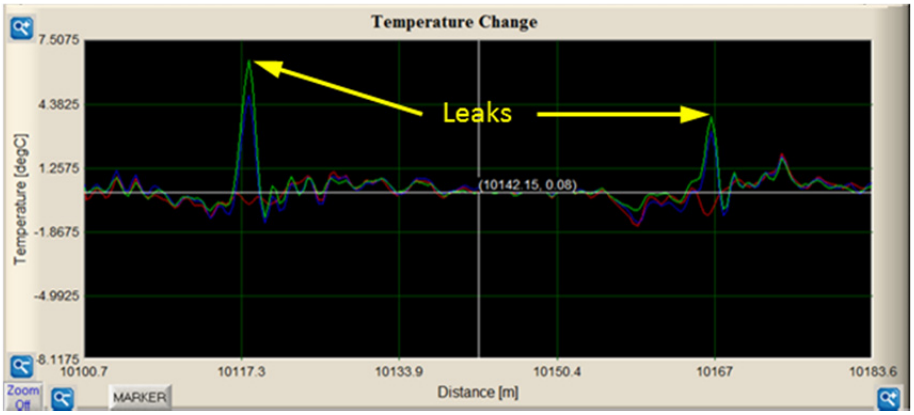

Figure 4. Large leakage detection from 1/8” orifice with 400 psi injection pressure, soil temperature before test: 85°F, line temperature: 115°F.

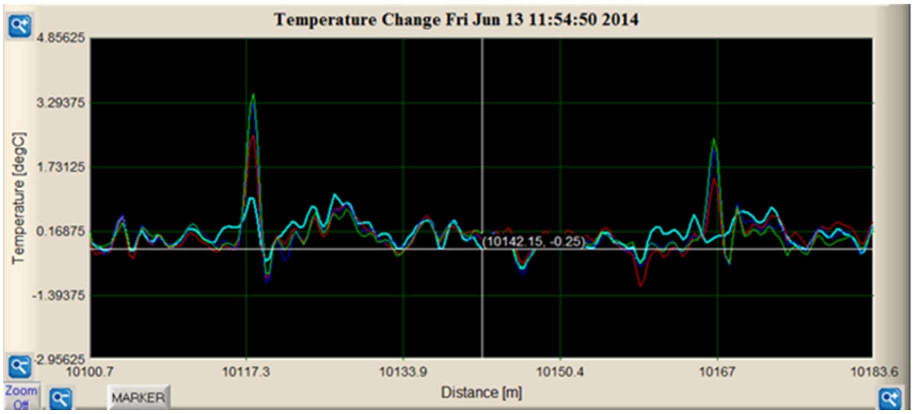

Figure 5. Small leakage detection from 1/8” orifice with 50 psi injection pressure, soil temperature before test: 73°F, line temperature: 90°F.

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