Fiber-Optic Sensors For Monitoring Pipe Bending Due To Ground Movement

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This article describes an installation of fiber-optic sensors designed to measure pipe bending due to ground movement at three sites on a 16-inch gas transmission line. The sour gas pipeline had failed in December 2004 from excessive forces related to ground movement. As temporary mitigation, the pipeline was daylighted to reduce the soil traction forces.

Before placing the pipeline back into conventional service, however, a comprehensive monitoring program had to be developed. During the time when the section of pipeline was daylighted, three linear and three coiled fiber-optic sensors were installed at each of three sites selected as part of a system designed to measure bending strains as large as 1%. The two types of sensors were placed in pairs approximately at the 12, 4, and 8 o'clock positions.

Conventional vibrating wire (VW) strain gauges were also installed for comparison purposes. Following pipeline re-coating and back-filling, visits to the site were made at approximately monthly intervals to gather data at conveniently located breakout boxes. The fiber-optic sensor system functionality is described and a comparison is made between the three techniques.

Canadian Pipeline

The installation was performed on a north/south-running section of Duke Energy Gas Transmission's (DEGT) 16-inch Silver Dahl pipeline near Fort St. John, British Columbia. The installation site is bordered by an east/west river as the terrain slopes downhill to the north. The combined effects of the sloping terrain and the nearby Blueberry River cause ground movement that requires the Silver Dahl pipeline to be periodically monitored.

When an FT Sensor is rigidly bonded to a structure, an FT Sensor monitor can be used to precisely track changes in strain that occur in the underlying structure. Changes in both the mechanical and thermal strain of the structure of interest are determined from these readings. Combinations of FT Sensors with different geometries are used to calculate and monitor pipe bending.

In this project, two types of FT Sensors monitor pipe strain in different strain regimes. Linear 1 m gauge length sensors installed along the longitudinal axis of the pipe were installed to monitor axial strains in the 0.01-1% strain regime; meanwhile, coiled 10 m sensors susceptible to both hoop and axial strain were installed to monitor smaller strains (< 0.01% strain). In addition to using fiber-optic sensors, spot-weldable VW strain gauges were added to independently measure mechanical strain along the axial direction up to the ~0.1% strain level.

FT Sensor Technology

Sensor Principle

The fundamental principle behind the FT sensor is the interference of low coherence light [1, 2]. The sensor system, as modeled in Figure 1, is comprised of two optical paths; an internal actuated reference path, and the external sensor. Each of the optical paths has a reflective surface at the end so that some of the light traveling down either path is reflected. As a result of the optical interference of white low-coherence light, an optical interferometric signal will be generated when the two optical path lengths are equal.

By actuating the optical path internal to the instrument until the two path lengths are made equal and an interferometric signal is detected, the optical path of the sensor can be measured. In practice, the length of the reference path can be varied mechanically by either stretching an internal optical fiber or creating a variable free-space optical delay.

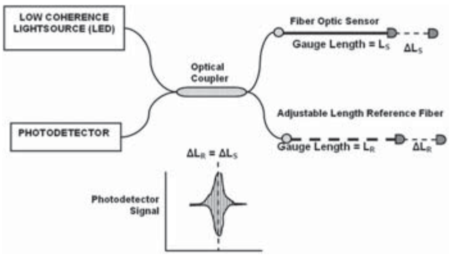

Figure 1: FT Fiber-Optic Sensor system schematic

Sensor Configurations

The sensor itself is made from conventional single-mode optical fiber. The small-diameter flexible fiber allows the sensor to be packaged into configurations that are suitable for monitoring many types of defects. Typical FT Sensor configurations include linear and coil arrangements. While other custom configurations and gauge lengths have been used in specialty projects, these two configurations can be used in the majority of applications. Figure 2 illustrates the geometry of linear and coiled FT Sensors.

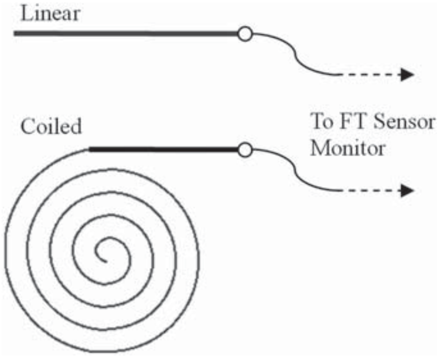

Figure 2: Linear and Coiled FT Sensors Sensor Monitoring

Sensor Monitoring

Due to the unique way that FT Sensors operate, their optical signals can only be demodulated using an FT Sensor Monitor (Figure 3). Currently, two monitor models are available. One is primarily targeted for continuous monitoring applications and is AC-powered; and the other is battery-powered and more compact, suitable for outdoor periodic monitoring applications. Total sensor displacements of over ±15 mm (±1,500 με for a 10 m gauge length sensor) can be monitored with either system. This dynamic range, combined with the sensor gauge length, defines the strain range measurable. As a result, gauge length and sensor configuration is selected during the project planning phase to meet specific project objectives.

Figure 3: FT 3410 (top) and FT 3405 Monitor for FT Sensors

For periodic monitoring applications, data acquisition is performed at the site with minimal operation required from supervising personnel. Data retrieval from the portable sensor monitor is performed through a USB connection to a PC. Data is transferred in a compressed, encrypted file with built-in data integrity safeguards. These features provide the trained end-user with secure access to site-specific data and easy to use charting and analysis tools.

Installation

FT Sensors were installed in June 2005 at three sites on the daylighted pipe following a tensile failure due to excessive ground movement. Sensors were rigidly bonded to the pipe using specialized epoxies. The epoxy was able to fully cure at ambient temperature after several hours. In other higher-temperature applications, different epoxies are used, permitting a faster cure time. At the same time, conventional VW strain gauges were installed nearby using spot-welding.

At each of the three sites installed with sensors, three 1 m linear FT Sensors, three 10 m coiled FT Sensors, and three conventional VW strain gauges were installed. This accounts for a total of 18 installed FT Sensors and nine VW strain gauges across three sites. Figure 4 shows the daylighted pipe with FT Sensors bonded to the exterior.

After the epoxy used to bond the sensors was allowed to cure, the pipe was wrapped to minimize exposure to the surrounding soil. Linear sensors were oriented parallel to the flow direction to allow easy comparison with conventional strain gauges, and were positioned at ~35°, 130°, and 230°. In this convention, 0° represents the 12 o'clock position of the pipe and positive rotation is defined by the right-hand rule and the flow direction (see Figure 5). VW strain gauges were positioned at 0°, 120°, and 240°; and FT Coil sensors were installed adjacent to each.

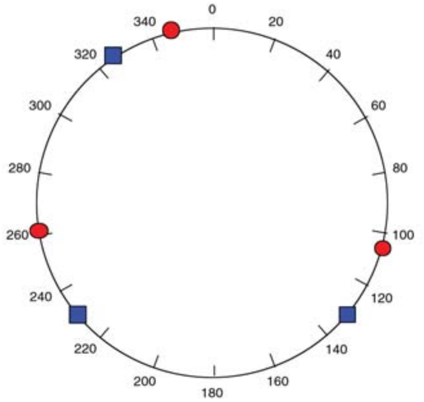

Figure 5: Angular location of FT Linear Sensors (blue squares), and FT Coil Sensors (red circles). Product flow was to the south.

In order to allow reading of the FT Sensors and conventional strain gauges, fiber-optic lead cables (3mm diameter) were housed within PVC conduit which led to pole-mounted surface break boxes (one per each of the three sites).

Data Collection

For most pipeline bending applications, periodic data acquisition is obtained through site visits with a portable FT Sensor Monitor. Data acquisition entails traveling to the breakout box with a battery-powered instrument, connecting the FT Sensor Monitor to the patch panel, and initiating the monitor to scan automatically. Data automatically obtained at one site over the course of a half hour can potentially gather more than 200 data points unsupervised. Data was first acquired in June 2005 by FOX-TEK personnel, since which time DEGT personnel have assumed responsibility for data acquisition.

Bending Analysis

Calculating strain due to pure bending on a pipe requires axial strain information from two sensors. In the case of deformations where axial strain is due to tension/compression in addition to bending, a third sensor is required.

Linear FT Sensors, when installed along the axis of the pipe, are only sensitive to thermal and mechanical strain in the axial direction. Temperature compensation is required to separate axial from thermal strain. In the case of the pure bending analysis, because the temperatures of all FT Sensors rigidly bonded to the pipe are approximately equal, absolute axial strain measurements will simply include an offset due to thermal strain.

By solving a system of equations, one can locate the neutral plane and separate the non-bending strain from bending strain. One can also calculate the bending direction through location of the neutral plane and determine that maximum bending strain (i.e. occurring 90° from the neutral plane). By convention, the bending vector points in the direction of the pipe bend, or the axis about which bending is occurring. The maximum bending strain is calculated using (1) as shown:

$$|\varepsilon_{MAX}| = \frac{\varepsilon_n}{\sin(\theta_n)} \quad (1)$$

In (1), n refers to any of the three sensors used, Ø defines the angle displacement of the sensor from the neutral plane, and ε_n is the observed bending strain.

Preliminary Results

Since the repair on the pipeline was conducted in June 2005, only small pipeline movements have been observed using the three monitoring techniques. The largest single strain reading observed as of September 2006 was ~600 με. Over this period of time, the VW strain gauges have explored 40% of their dynamic measuring range, while the FT Linear sensors have only explored a mere 1%, illustrating the advantage of a customizable gauge length.

Figure 4: Photo of daylighted pipe with exposed, bonded sensors. From left to right, visible sensors are a VW strain gauge, 10 m coiled FT Sensor, and a 1 m linear FT sensor.

In the results shown here, data acquired in September 2005 has been used to form the baseline.

Bending directions and maximum bending strains were obtained using data from the coiled FT Sensors, the linear FT Sensors, and the VW strain gauges. Examination of the calculated maximum bending strain, bending angle, and thermally compensated axial strain show good agreement between all three techniques at all three sites. Figure 6 shows the results obtained at Site #2.

While the trends in Figure 6 all track one another (as seen in the movement observed in March 2006), offsets between them are apparent. These offsets can be understood by considering the differences in the active sensing area of each of the technologies. The VW strain gauges have an active area of ~10 cm and only detect strain in the axial direction. The FT Coil Sensors, while approximately the same size in one dimension, are circular and are also susceptible to hoop strain.

The FT Linear Sensors, however, stand out, having a much larger gauge length (1 m). This larger gauge length yields two significant benefits: (i) they inherently average pipe strain over a larger representative area; and (ii) being longer, they are less likely to miss an event or report readings exaggerated, or masked, by local abnormalities on the pipe's surface.

Conclusion

Fiber-optic FT Sensors and conventional VW strain gauges were installed and are being monitored at three sites on the 16-inch Silver Dahl pipeline near Fort St. John. The equipment and expertise needed to acquire FT Sensor data, which can be used to calculate strain, has been transferred to DEGT. Several data sets have been successfully acquired over

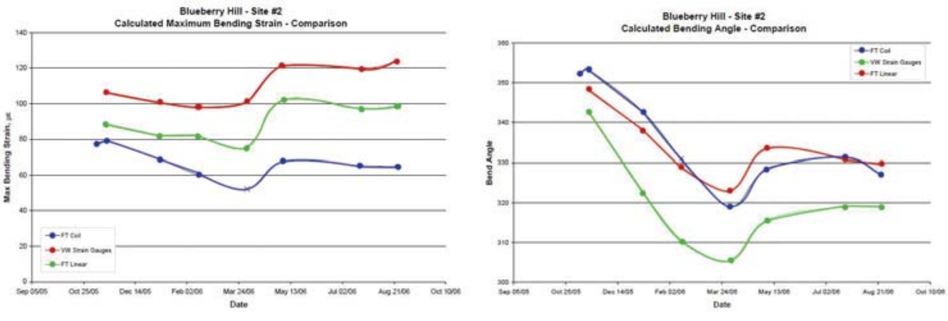

Figure 6: (Left) Maximum bending strain, and (right) bending angle of pipeline at Site #2, located ~100 meters uphill from the Blueberry River.

the course of a year and have been used in an analysis of bending deformations.

A comparison of the data obtained using VW strain gauges and FT Sensors show that, while the techniques are quite different, both methods result in similar trends. Moreover, the FT Linear Sensors offer the additional benefits of a larger dynamic range, and a larger, customizable gauge length. These results demonstrate the functionality and successful operation of FOX-TEK's FT Sensor technology for buried pipeline bending applications due to ground movement. Such monitoring programs can lead to increased safety, increased throughput, fewer unplanned shutdowns, and a reduced threat of environmental damage by providing insight into the timing and location of pipe bending. ***P&GJ***

ACKNOWLEDGEMENTS:

The authors would like to thank the American Society of Mechanical Engineers (ASME) for allowing reproduction of this article from the Proceedings of the 2006 International Pipeline Conference.

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