OPTICAL FIBER SENSORS FOR SUBSEA AND TOPSIDE ASSET INTEGRITY MONITORING APPLICATIONS

VICTOR SERVETTE
OPTICAL FIBER ENGINEER, CEMENTYS, HOUSTON, TEXAS

VINCENT LAMOUR
CHIEF TECHNOLOGY OFFICER, CEMENTYS, HOUSTON, TEXAS

KENNETH BHALLA
PRINCIPAL, STRESS ENGINEERING SERVICES, HOUSTON, TEXAS

RYAN BRISTER
TEST ENGINEER, STRESS ENGINEERING SERVICES, HOUSTON, TEXAS

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ABSTRACT

Asset integrity monitoring is becoming a critical activity as Oil & Gas operators need to secure their existing production assets and extend their service life. The last decade happened to be a turning point for sensing technologies as deeper subsea oil fields and intelligent oil wells required the extensive use of optical fiber sensors. As a result, optical fiber sensor technologies are now matured and off-the-shelf solutions for offshore and subsea asset integrity monitoring.

Fiber optics differs from other monitoring technologies by being totally passive: this means there is no need for subsea electronics or batteries power, making it an ideal choice for long term offshore and subsea asset integrity monitoring. Added to easy real-time communication, high multiplexing capabilities and distributed sensing, optical fiber brings new possibilities to existing traditional sensing systems.

Optical fibers are also extremely robust and, when deployed correctly, has a lifetime of more than 25 years, such as in the telecommunication industry.

Different optical fiber sensor technologies have been developed for Oil & Gas applications, creating a wide diversity of sensing capabilities, for both punctual (Fiber Bragg Gratings) and distributed sensing (Distributed Temperature Sensing, Distributed Strain Sensing, Distributed Acoustic Sensing, Distributed Pressure Sensing).

In this paper we present the latest optical fiber sensor monitoring solutions and applications for offshore and subsea asset integrity monitoring. The assets studied include Hulls and Topside Structures (Structural Health Monitoring), Risers (fatigue monitoring on Touch Down Zone and Hang-Off point), Mooring Chains and Turrets (load monitoring by load cells or load shackles), and subsea tiebacks and umbilicals (distributed monitoring of both temperature and strain for subsea leak detection and life of field monitoring).

Keywords: SNAME, Offshore, Symposium, Optical Fiber, Fiber Bragg Grating, DTS, DAS, DSS, Raman, Brillouin, Rayleigh, Life of Field, Asset Integrity Monitoring, Structural Health Monitoring
INTRODUCTION

Optical fiber sensor is creating a revolution in the sensor market, by allowing new measurement capabilities. Its intrinsic properties make it very well adapted to the offshore and subsea environments:

- Passive sensors: the sensors do not need any electronics or batteries to send out measurements
- No inline power : well adapted for topside Class 1 Div 1 environments
- Good for static and dynamic measurements : 25 years without drift and up to 25 kHz for FBG sensors
- Not affected by ElectroMagnetic (EM) field: sensors can be implemented near high voltage or strong electromagnets
- Very high multiplexing possibilities: typically more than 50 000 sensors on a single fiber for distributed sensing
- Non-intrusive: a fiber is 125µm thick, only one fiber is needed
- Frequency measurements: high signal to noise ratio, insensitive to inline losses or de/reconnections

For comparison, a classic resistive strain gage may be sensitive to moisture ingress and EM fields, may needs to be recalibrated (offset drift) and typically requires 4 wires per gauge.

In this paper, we first present the two major technologies used for optical fiber sensor monitoring: Fiber Bragg Gratings “FBG” for discrete measurements and Optical Time Domain Reflectometry for distributed measurements. Then we present the different applications of optical fiber sensors in the Oil&Gas offshore and subsea industries.

TECHNOLOGIES

A wide range of optical fiber sensors were developed for different industries. In this paper, we focus on the two major technologies that has been used for the last decade in the Oil&Gas industry: Fiber Bragg Grating based sensors and Optical Time Domain Reflectometry based sensors.

1. What is an optical fiber?

In order to understand optical fiber sensors, one must first look at an optical fiber. An optical fiber is a flexible string made of extruded glass capable of transmitting light from one end to the other. It is extremely small (125µm, thinner than an hair) and totally passive: it does not transport energy other than light and does not need any power supply. The core fiber can be protected within a cable, making an optical fiber cable just as strong as a conventional electric cable.

In order to confine the light, an optical fiber is made out of different layers of silica, with different optical indices (see Figure 1). The difference of indices between the core and the cladding ensures that the light will stay within the core of the fiber. The size of the core can change, making the fiber either single-mode (core of typically 9µm) or multi-mode (typically 50 or 62.5µm). The fiber is then protected by a buffer and inserted inside a cable, within different thickness and protection depending on the application.

![Cross section of an optical fiber cable](image)
2. Fiber Bragg Grating Sensors

Fiber Bragg Grating (FBG) Sensor is the most common type of optical sensors, used for a wide variety of applications. A FBG is an optical element that can be implemented locally inside a fiber. It has the property of reflecting only one wavelength while transmitting all the others. The reflected wavelength depends on the properties of the fiber locally (strain and temperature).

It is composed of a small periodic variation of the optical index inside the core of the fiber. The frequency of the reflected wavelength is directly linked to the period of the grating (Equation (1), Figure 2), so one can easily see that a change in the period of the grating (due to either mechanical or thermal effects) will change the frequency of the reflected wavelength. They are similar to electrical strain gauges in their response, this is why they are often referred to as optical strain gauges.

![Fiber Bragg Gratings](image)

Figure 2: Fiber Bragg Gratings

$$\lambda_B = 2n_e \Lambda_B$$ (1)

Where $\lambda_B$ is the wavelength of the reflected light, $n_e$ the effective index of the fiber and $\Lambda_B$ is the grating period.

3. Distributed Fiber Optic Sensors by Optical Time Domain Reflectometry measurements

Distributed Sensing led a major breakthrough in the optical fiber sensing technologies: a single telecommunication fiber is able to provide measurements typically every foot for several miles! No punctual sensors are necessary, the fiber itself reacts to its environment and sends the information back to both ends, it acts both as sensor and as a communication device.

This technology is based on Optical Time Domain Reflectometry, meaning that it analyses the light backscattered from a fiber (Figure 3). A laser pushes a short single frequency light pulse through the fiber, that pulse is backscattered in the fiber due to different physical phenomena (Rayleigh, Raman, Brillouin backscatterings), this backscattered light is then analyzed. The location of the information is known thanks to the time of flight of the backscattered light (in the same way a radar computes distance).
The backscattered light is analyzed in frequency thanks to an optical spectrometer. The received spectrum contains interaction peaks due to different physical phenomena (see Figure 4):

- The Rayleigh peak has the same frequency as the laser pulse. Its intensity will vary with local vibrations and temperature
- The Brillouin peaks will see their frequency shifted due to both local temperature and strain changes
- The Raman peaks intensity will vary with temperature

By analysing the different peaks, a single fiber can serve as a distributed sensor for temperature (DTS), strain (DSS), vibration (DVS) and acoustics (DAS).

4. Case study : comparison between optical and electrical strain gauges for pipeline fatigue analysis

In collaboration with Stress Engineering Services (SES), several tests were performed to compare optical strain gages to classic electrical strain gauges. These tests were conducted at the Stress Engineering Facility in Houston. A fatigue test sample of pipe was instrumented by SES with several electrical strain gauges using their regular procedures. We then installed 2 FBG StrainLux gages: one for strain and one for temperature measurements.
This test setup allowed us to make the sample vibrate at the desired value of cyclic strain. Multiple tests were performed on the sample as to isolate different measurement artefacts. The first test was a simple baseline measurement, to measure the noise level of each gage. During this base line measurement, the sample is at rest. The results are shown in Figure 6.

One can clearly see that on this setup, optical gages have a lower noise level than the electrical gages (around 0.3µstrain versus 1.5 µstrains).

Several strain tests were done, for different values of enforced oscillating strain, by vibrating the sample close to its natural frequency. Figure 7 gives an example of results obtained:
Figure 7: Strain measurement comparison

The measurements obtained with the optical gage is in accordance with the strain values measured by the electrical gages.

The final test presented in this paper is the influence of electromagnetism (EM) noise on the measurements. For this, a powerful magnet was moved close to the gages while the test sample is at rest. Figure 8 shows the influence of EM fields for both technologies.

Figure 8 clearly shows the effects of EM fields near electrical gages: the noise level drastically increases and creates erratic measurements. On the other hand, we can see that the optical gage isn’t influenced. This makes optical fiber sensor, the technology of choice when measurements are need in strong EM fields, such as close to electric pumps, valve or generators. This is especially true at low strain levels.
APPLICATIONS

In this section, we will detail how optical fiber sensors can be used for Asset Integrity Monitoring in the Offshore industry. For the sake of clarity, we present the field applications from the subsea reservoir to the offshore platform (see Figure 9).

Figure 9: Fiber optic sensors applications in Offshore Industry (source: Cementys.com)

1. Downhole Applications

In the reservoir, several parameters are important to monitor in order to optimize the product flow and to enhance oil recovery. Temperature and pressure are the most common measured parameters. Today, the majority of pressure and temperature cells use embedded electronics and quartz technologies. They give good results but their use may be limited by several factors: they cannot work permanently in high temperatures (>200°C or 390°F) and are difficult to multiplex on a single line.

For this reason, several companies developed pressure and temperature cells working on FBGs. These cells allow measurements in high temperatures with direct communication. The FBG is used as an optical strain gauge, attached to a sensitive element subject to pressure.

Distributed Fiber Optic Sensor measurements are also commonly performed in the downhole fields. Both temperature and acoustics can be monitored using an optical fiber cable deployed in the well by using DTS and DAS interrogators. The results were found to be extremely helpful during well completion and operation phases, this is why more than 10 000 wells (mostly onshore) have been equipped with distributed Fiber Optic Sensing measurement systems (Jacobs 2015).

The major advantage for using optical fiber sensors in subsea downhole applications relies on measuring remotely and permanently passive downhole sensors with very long existing umbilical lines (over 10 miles). The relatively high cost of optical wet mate connectors is still a limiting factor for Optical Fiber Sensor deployment on Subsea Wells.
Figure 10: Example of a ½” Optical Fiber Downhole Pressure/Temperature gauge for High Temperature / High Pressure Oil Fields.

2. **Subsea tree applications**

   Subsea trees, BOP stacks are critical components, subjected to important loads and vibrations from the riser system. A failure of critical components leads to safety and environmental issues. Structural Health Monitoring can be typically performed through 3 longitudinal strain sensors allowing vibration and stress analysis. If needed, a “wet mate” connector, allowing subsea connection and disconnection of the optical line, can be installed so the sensors can be interrogated by a ROV, for periodic survey readings.

   Other Process sensors such as Pressure sensors, Flowmeters, thermometer or accelerometers can use the FBG technology to be integrated to existing optical telecommunication subsea networks without any power.

3. **Subsea tiebacks and flowlines.**

   Subsea tiebacks and flowlines are critical assets that are difficult to inspect. They need to be engineered as to make sure the pipe will not be obstructed by the transported product. The classic solution today is to double the line, to be able to send pigs for cleaning and be sure that one will be always available if the other gets clogged due, for example, to hydrate formation.

   To remedy this issue, new pipes have been developed to increase the product temperature, either passively (insulated layers on the pipe) or actively (electrically trace-heated pipes). In both cases, it is important to measure the distribution of the temperature along the pipe: it will help production by reducing the risk of clogging and, in the case of heated lines, it will make sure the system is functioning correctly.

   Distributed Temperature Sensing is very well adapted to this application: the fiber cable can easily be implemented on the pipe before its installation, to be connected to existing communication lines once laid. An interrogation box topside will then give out temperature data all along the line by connecting it to the fiber (DNV 2009).

   Such a system can also be used to see and prevent the apparition of lateral buckling: by interrogating the fiber with a Brillouin based interrogator for Distributed Stress Sensing, one can see the progressive apparition of stresses inside the line. Those stresses being linked to the lateral buckling of the tieback, proactive measures can be put in place to make sure the design stress are never exceeded.
Corrosion

Corrosion is omnipresent in the subsea and offshore environments. It is important to control it to ensure the durability and reliability of all the equipment installed. Today, several solutions exist to monitor the corrosion progress, for example cathodic protection monitoring or the use of coupons. The challenge is that those elements require an inspection to know if they need to be replaced. This can be costly, especially if the coupon is hard to reach (for example a coupon installed on a production tubing, where the whole line needs to be brought up to inspect it).

FBG sensors can be used for corrosion monitoring thanks to their very low drift in time (no effect of moisture ingress or electromagnetic noise). If engineered and installed correctly, the instrumented coupon will relieve stress as its section is getting thinner due to corrosion, this stress relief can be monitored by an optical strain gauge. This type of measurements allows conditioned based maintenance approach, instead of a preventive maintenance strategy, and thus a lower maintenance cost as well as increasing the safety of the system.
5. Risers

Risers are equivalent to a field’s highway: they link all the small oil routes at the seabed to structure topside. All the oil produced from a field will go through this complex structure (rigid or flexible risers), its health is thus critical. Today, most of the riser service lives are computed through cumulative fatigue models. Additionally, there are also sensors on the market to monitor them (mainly the hang of point), using either vibrating wire technology, strain gages or LVDT extensometers. They have been widely installed and give good results but have limitations: being electronic based sensors they need subsea power, meaning the batteries need to be changed by an ROV periodically for long term permanent operation. The technologies can also be limited in dynamic to a few Hertz, making the measurement of Vortex Induced Vibration difficult (DNV 2008).

Different companies are working on optical sensors for riser monitoring to avoid those limitation. An FBG based sensor installed at the hang-off point would not need any subsea power and electronics, and could give real time measurements up to 25kHz. As existing sensors, they could be clamped to an installed riser or fitted in the engineering design.

Even though they have a lot of advantages, solutions still need to be developed before an installation can take place: in order to function, the sensors need a continuous optical line to the platform. This can be done either by installing a dedicated umbilical, or by connecting the line to an existing optical line used for telecommunication. Both solutions have their pros and cons and need to be developed and properly installed.

Another critical part of the riser is the Touch Down Zone (TDZ): with tides, waves and other environmental factors, the location of the touch down point may vary up to several tens of meters. This can mean strong localized stresses and possible location of high fatigue damage accumulation. An FBG solution could be well adapted, thanks to its high multiplexing capabilities: an array of optical gauges can be deployed along the TDZ, allowing a complete stress analysis of the zone with low intrusion to this critical part, all the sensors can be multiplexed on a single fiber. The array can be connected to the Subsea Umbilical Termination Assembly (SUTA) via a patch-cord and wet mate connectors once the riser is installed. There, an existing communication optical fiber umbilical line is used to link the sensors to the topside.

Finally, we can monitor the shape of the riser with time. Currents and temperature gradients can greatly affect the riser and create localized weak points. Distributed Strain Sensing (DSS) can be used to know the strains all along the riser. These distributed strain values could be computed to displacement by integration and thus giving the wanted shape. Here-again solutions need to be qualified before an installation can be done. The main issue would be the deployment of the optical fiber on an existing riser. Two solutions are thought-of, either by clamping a cable straight down the structure (piggy-back configuration), or twisting the cable regularly down the riser (helix configuration). The length of the riser could also be an issue: displacement being computed by integration of strain, the calculation error will increase rapidly without reference points.

6. Mooring chains and turrets

There are few sensors available on the market for mooring chain load or tilt monitoring applications. They can mainly be divided into three main categories: smart shackles, load cells or tilt sensors.

Smart shackles work by monitoring the stress inside a bended pin of the shackle to come back to load. They have to be installed on the first chain link and are responsible for the full load of the chain. Fiber Optical Shackles will give an absolute value of the load on the mooring chain without any moisture effect or electronic drift. This type of smart shackle has to be planned in advance before the chain installation.

The load cells differ from shackles by being installed on the chain stopper structure. A typical optical Load Cell will perform permanently in offshore environments without recalibration. Another possibility is to install optical strain gages on several links of the chain. Clamped to the link, they measure the variations in load with time.

Both smart shackles and load cells already exist on the market, but working with classic electrical gages. This means an important drift with time and a high dependency on environment (humidity, temperature…). These issues make the items unreliable after a few months of measurements. Transforming those items by including optical fiber gages would help this reliability issue. This is why several companies are working on the development and installation of such sensors.

A local measurement of tilt also gives valuable information on the load of the chain: most of the mooring systems use a catenary disposition, where the tilt of a known point is directly linked to the load of the line. This system can be either in 1 or 2 directions, to see the influences of currents. Those measurements can give an absolute value of the load, as well as information in load change with time. Once again, fiber optical technology has the advantage of not
having any battery or electronics subsea: the sensor is totally passive and the measurements are taken real time thanks to an telecom optical cable connected to the platform.

In all applications, most sensors used in Offshore applications use classic electronic gages. This means that the measurements will deteriorate rapidly due to drift of the sensors and to their dependence on their environment (humidity, temperature, loses on the line) after only few months of operation.

This issue can be avoided by switching the electronic technology to optical FBG technology. The sensitive elements need only very little changes to be adapted to fiber optics.

7. Structural Health Monitoring

For safety reason, it is important to monitor the long term asset integrity of the topside structures. To do so, Sensors can be implemented on specific regions of the structure to get additional data and make sure the mechanical behavior is as it was predicted by the initial model.

In the case where service life of a platform needs to be extended, how can you be sure it is in good health? The initial model cannot be used anymore, and the lack of data concerning the structure makes it very difficult to ensure its integrity from simulation only.

Optical sensors can be helpful in such a case: by installing several sensors at key positions, one can compute the frequency of resonance of the different modes of vibration, thanks to a vibration analysis. These sensors can be implemented at the end of the initial life expectancy of the structure, and make sure the frequencies do not vary with time: a change in frequency means a behavioral change of the structure, thus aging. This method doesn’t give absolute integrity on the structure, but it is monitoring the changes over time (slow aging process).

Sensors using different technologies can be used for this application, but FBG based sensors are well adapted: being totally passive, they can be implemented on the structure without major changes. Other technologies might have trouble adapting to class 1 div 1 environments (highly explosive environments). All the sensors can be multiplexed on the same line, making the cable line non-intrusive. Lastly, they are long term sensors capable of measurements for several years without drift, and with high frequency measurements adapted to vibration analysis.

CONCLUSIONS

A multitude of industrial sectors will benefit from the new optical fiber sensor technologies. From the well to the topside structure, optical fiber sensor can bring complementary and previously impossible data to improve safety and production of Oil&Gas assets. Such long term monitoring solutions can provide near-term and long-term cost-saving benefits such as:

- Supervised lifetime extension for existing assets, which are candidates for replacement
- Asset Integrity Monitoring during installation, commissioning and early life, reducing Vessel Time when inspection / expertise is needed.
- Risk Based Management and Condition Based Maintenance during service life

Although the optical fiber technology is fully developed and already in place in other industries (civil engineering, nuclear, health sciences…), installation challenges slowed the implementations of optical fiber sensors in the Offshore industry. Most of those challenges are getting resolved (wetmate connectors, optical pass-through assemblies, optical umbilicals and jumpers…), meaning that the offshore industry will soon benefit from this Asset Integrity Monitoring enabling technologies.
REFERENCES


