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STRAIN SENSORS FOR DEEPWATER APPLICATIONS

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Abstract

The evaluation of the fatigue performance of deep-water risers requires the monitoring of the dynamic and static strain levels undergone during the whole lifetime. ENI E&P, SMARTEC and Tecnomare have developed and qualified a comprehensive solution for riser strain monitoring based on fibre-optic technology.

The system is composed of: a) underwater part, b) interconnection system and c) surface equipment. In the underwater part, riser segments are instrumented with four strain sensors, installed parallel to the riser axis and arranged at 90° angles around the riser circumference. The sensors measure the average strain over a measurement basis between 0.5m and 5m, typically 2 m. This disposition allows the evaluation of axial and bending strains in both orthogonal directions. This information is available also in the case of failure of a single sensor. Through a junction box, sensor signals are transferred to a standard underwater cable (the interconnection system), up to 5 km long. The surface equipment, located in a convenient location in the platform control room, consists of an interferometer that allows both dynamic and static strain measurements.

ENI E&P has developed and tested a prototype version on a shallow water riser in the Adriatic Sea for two years [1]. Based on this experience new sensors have been developed together with special technical solutions for deep-water applications, by ENI E&P, SMARTEC and Tecnomare. Between 2002 and 2003 the system has been qualified on a riser mock-up in hyperbaric chamber (up to 360 bar) and on a full-scale riser section in controlled laboratory conditions.

This paper presents the design and performances of the components and the results of the qualification tests.

INTRODUCTION

The exploration and production of offshore oil fields is extending to increasingly deep waters. Current plans and projects aim to install and operate platforms with a water depth between 1500 and 3000 m. This puts high demands on the risers, i.e. the tubes that connect the sea bottom to the platform and are used to perforate, extract and export oil. These risers are generally built in steel and hang freely in the deep water. Two main types of riser exist: vertical and catenaries. Vertical risers are used for drilling and production and connect the platform to the wellhead situated almost vertically below the platform. Catenaries risers are used for oil export or production from wells far from the platform. These risers are vertically hung to the platform on one side and lie horizontally on the sea bottom on the other side.

One of the main design limits for risers is fatigue. For vertical risers, the more fatigue-prone areas are the connection point between the riser and the platform and the connection to the wellhead. For catenaries risers, the touchdown area is also critical for fatigue. The design and evaluation of the fatigue performance of deep-water risers is usually addressed through simulations and calculation of strain levels obtained by acceleration measurements. These acceleration and displacement measurements are usually logged, retrieved and processed off-line, limiting their usefulness for operational purposes. It would therefore be beneficial to rely on a permanent and in-line monitoring system, which directly measures the strain levels experienced by the riser in its most critical zones, during its whole lifetime.

SYSTEM DESCRIPTION

ENI E&P, SMARTEC and Tecnomare have developed and qualified a comprehensive solution for riser strain monitoring based on fibre-optic technology.

The system is composed of an underwater sensing network, an interconnection system and appropriate surface equipment. These will be described in the following paragraphs.

Underwater equipment

In the underwater part, riser segments are instrumented with four fibre-optic strain sensors, installed parallel to the riser axis and arranged at 90° angles around the riser circumference. The sensors measure the average strain over a measurement basis between 0.5 m and 5 m, typically 2 m. This disposition allows the evaluation of axial and bending strains in both orthogonal directions. This information is available also in the case of failure of a single sensor. The sensors are based on the interferometric principle and allow the measurement of both dynamic and static strain, thanks to the use of a temperature-compensation fibre. The sensors are encapsulated in a glass fibre-reinforced polymer ribbon that contains both the bonded strain measuring fibre and the free temperature reference fibre. The composite ribbon is cemented and clamped to the riser surface (see Figures 1 and 2).

Figure 1. Sensors glued and clamped to a riser section.

Figure 2. Layout of the sensors on a riser section with external protection.

Interconnection system

Through a watertight junction box, sensor signals from four to eight sensors are transferred to a standard underwater cable (the interconnection system), up to 5 km long. Each measurement area is connected through a separate cable, but the cables can be assembled in a bundle to facilitate installation along the riser during its deployment.
Figure 3 shows an implementation of the interconnection box between the single sensors (lower end) and the multi-fibre cable (upper end). Figure 4 depicts an alternative design.

Figure 3. Watertight junction box with connector and optical cable.

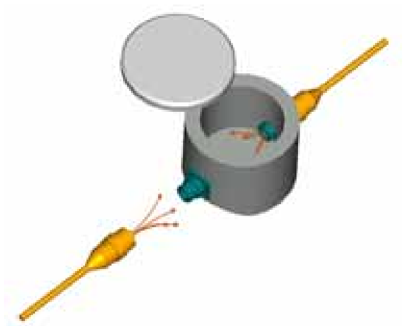

Figure 4. Alternate design of the underwater junction box. (Not included in the qualification project)

Surface Equipment
The surface equipment, located at a convenient location in the platform control room, consists of an interferometer that allows both dynamic and static strain measurements (see Figure 5). The SOFO dynamic [2,3] measurements can be performed at frequencies of 100 Hz and more, and offer a strain resolution of the order of 0.01 microstrain. The

SOFO static [4] measurements feature an excellent long-term stability, with a drift below 5 microstrains over multiple years of operation.

The SOFO static measuring system is based on the principle of low-coherence interferometry (see Figure 6). The infrared emission of a light emitting diode (LED) is launched into a standard single-mode fibre and directed, through a coupler, towards two optical fibres mounted on or embedded in the structure to be monitored. The measurement fibre is in mechanical contact with the structure itself and will therefore follow its deformations in both elongation and shortening. The second fibre, called reference fibre, is installed free nearby. Mirrors, placed at the end of both fibres, reflect the light back to the coupler that recombines the two beams and directs them towards the analyzer. This instrument also contains two fibre lines and can introduce a well-known path difference between them by means of a mobile mirror. On moving this mirror, a modulated signal is obtained on the photodiode only when the length difference between the fibres in the analyzer compensates the length difference between the fibres in the structure better than the coherence length of the source (in our case some hundreds of mm). Each measurement gives a new compensation position reflecting the deformation undergone by the structure relatively to the previous measurement points.

The Reading Unit can therefore be disconnected and used to monitor other fibre sensors and other structures. If multiple sensors need to be measured automatically, an optical switch is installed. The SOFO unit is capable of storing measurements and later transfers them to the data acquisition PC via a cable or a modem.

The SOFO Dynamic reading unit allows measuring SOFO sensors at high frequencies. One reading unit can be used to demodulate up to 8 channels. Multiple units can be combined when higher channel counts are needed. The SOFO Dynamic reading unit can be used in conjunction with the same SOFO sensors used for static measurements. The SOFO Dynamic reading unit is based on a heterodyne low-coherence interferometer operating at 1550 nm (see Figure 7). The optical signal is phase modulated by the demodulation interferometer. After detection, the reading unit tracks the phase modulation introduced by the sensors and converts it into a displacement. The resulting deformation is available in analog form on the analog outputs or in digital form on the USB connection that can be used to transfer the measurements directly to a PC for storage and further analysis. The measurements are relative and the zero point is lost on power off, but can be recalibrated using the SOFO Static reading unit.

Figure 5. SOFO system for static and dynamic measurements.

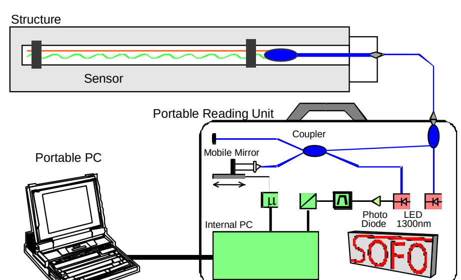

Figure 6. Setup of the SOFO system used for static measurements.

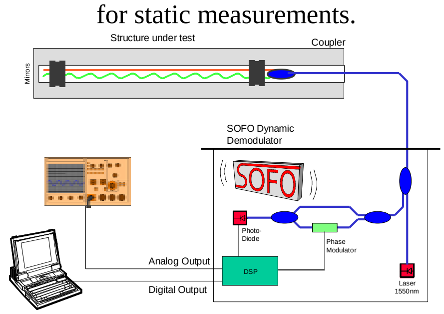

Figure 7. Setup of the SOFO system used for dynamic measurements.

System Performances

The main characteristics of the system are listed in Table 1.

Table 1. Characteristics of the system

Strain sensor technology	Fibre-optic interferometric sensor
Strain sensor gauge length	2 m (on request 0.5 to 5 m)
Sensors pro instrumented section	4
Maximum depth	3.000 m / 360 bar
Strain resolution for dynamic measures	0.2 $\mu\varepsilon$ @ 10 mHz, 0.01 $\mu\varepsilon$ @ 1 Hz
Dynamic range	1 mHz to 100 Hz
Strain resolution	1 $\mu\varepsilon$ for static measurements 0.01 $\mu\varepsilon$ for dynamic measurements
Temperature sensitivity	<1 $\mu\varepsilon$ / °C

The proposed sensor system offers the following benefits, especially in comparison with solutions based on conventional strain gauges or short-gauge fibre-optic sensors (e.g. fibre Bragg gratings):

- The use of long-gauge sensors simplifies the installation on the riser and does not require any accurate preparation of the surface.
- Since the sensors measure the average strain over a 2 m gauge length, the measurement is more representative of the riser strain state rather than local material properties. Local changes in the metal or coating mechanical properties do not affect the measurement.
- The system offers very high strain resolution (0.02 $\mu\varepsilon$) and dynamic range. This allows the use of the same sensing system for fatigue analysis and for the analysis of small strains.
- The sensors present an excellent long-term stability and durability allowing the comparison of strain states during all phases of the riser's life, from manufacturing to deployment and use.
- Each sensor is individually connected to the surface equipment through the use of multi-fibre cables. This offers the best possible level of redundancy since in no case the failure of one sensor will affect the performance of the others. On the other hand, the use of multi-fibre cables allows the installation of a reduced number of lines. Reliability and redundancy are therefore higher than in the case of multiplexed fibre-optic systems.
- The strain and temperature sensors are based on fibre-optic technology and are therefore totally passive. No electrical connection, power supply, amplifiers or data acquisition systems are necessary and all opto-electronic components are installed only at surface. The sensors do not require maintenance; they have neither moving parts nor components subject to wear or corrosion. Long-term reliability is greatly enhanced compared to electrical transducers.
- The system is highly failure robust, since each sensor is connected to the surface using a dedicated optical fibre.
- The strain and temperature sensors are pre-encapsulated into a fibre-reinforced polymer profile and are individually tested before installation in a pressure and climatic chamber, ensuring higher reliability compared to directly mount electrical or optical strain gauges.
- Each measurement area (4 off sensors, J-box, one fibre interconnection cable) is pre-assembled in an onshore facility.
- All underwater optical connections are realized inside pre-qualified and tested junction boxes based on proprietary technology. No underwater optical connection is used.

SYSTEM QUALIFICATION

A prototype version has been tested on a shallow water riser in the Adriatic Sea for two years giving excellent results in terms of performance and reliability [1]. Based on this experience, new sensors have been developed to address the specific issues related to deep-water applications. Between 2002 and 2003 the system has been qualified on a riser mock-up in hyperbaric chamber (up to 360 bar), as shown in Figures 8 and 9, and on a full-scale riser section in controlled laboratory conditions. The hyperbaric chamber tests were designed to test the survival of all sensing and interconnection components to the extreme pressures and to multiple pressure cycling. The full-scale tests aimed to the comparison of the static and dynamic strain levels measured by the new sensors with those measured by independent reference sensors. Both tests demonstrated the performance and reliability of the system and its suitability for the intended application.

Figure 8. Hyperbaric chamber with optical fibre feedthrough and underwater cable detail.

Figure 9. Installation of the instrumented riser section in the hyperbaric chamber.

In order to verify Sensor Tapes behaviour and performance under simulated operational mechanic conditions, Full-Scale Tests were performed. During these tests the following parameters were monitored:

- Sensing Tapes global behaviour as well as behaviour of each component (observation of damaging of components – tape, optical fibres, mirrors, metallic tube,)
- Sensing Tapes measurements reliability
- Reliability of adhesion of the Sensing Tapes to the riser (mechanical interaction between the Tapes and riser)

The tests were carried out by installing 2 m-long sensors on a 6 m section of steel tube subjected to 3-point bending (see Figures 10 and 11). The test reproduced the maximum level of strain expected in real applications.

Figure 10. General view of the full-scale test setup.

Figure 11. Detail of the installation of the sensors on the full-scale 6 m-long riser section.

Test Results

Figure 12 shows the results of one of the test runs performed on the riser section in hyperbaric chamber. Two types of tests were performed: with closed end-caps (i.e. with air inside the riser section) and with open end-caps (i.e. the same water pressure inside and outside the riser section). The test marked O corresponds to a cycle to 250 bar; tests P, Q and R correspond to cycles between 0 and 300 bar. Test T is a cycle to 360 bar. Test S is a long-term test at 300 bar. The small observed variations are correlated to water temperature changes associated with daily variations of ambient temperature that were monitored in parallel with the test cycles. Finally the tests U and V correspond to tests at 360 bar after removing the end-caps of the riser section. Sensing tapes 1 and 2, respectively 3 and 4 used different pressure compensating techniques and therefore present different responses to pressure. The results are in agreement with the theoretically predicted strain levels. It is to be noted that in a real application the pressure will be practically constant during operation.

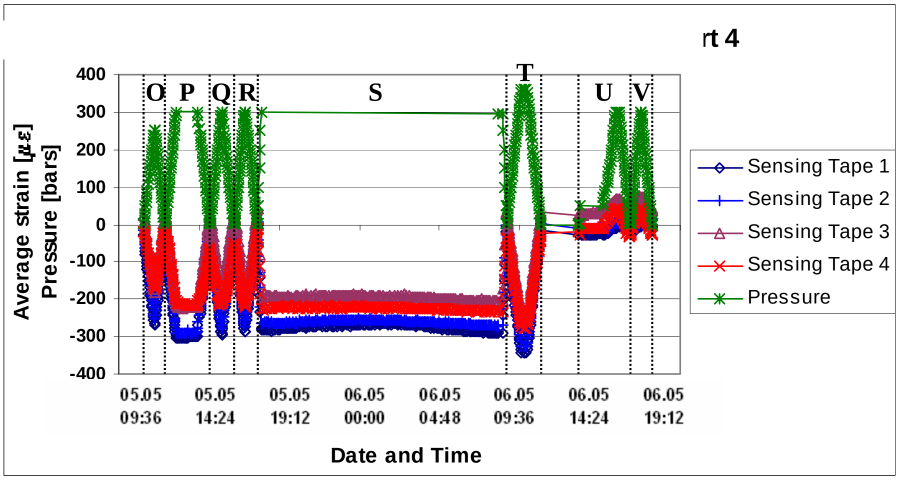

Figure 12. Hyperbaric chamber testing results: Pressure cycling with closed and open riser section.

These results show that the sensors and all interconnection systems can be used safely at pressure of up to 300 bars and perform according to the specifications and the predicted response of the riser scaled model.

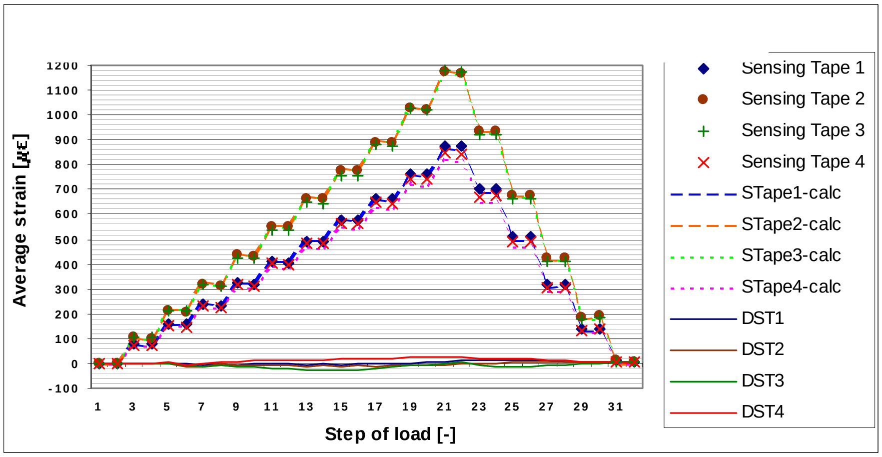

Figure 13. Full-scale testing results: Comparison of measured and theoretical strains and residual differences.

Figure 13 shows the testing results for the full-scale test. The riser section was loaded stepwise and the deformations of each of the four sensors recorded. The different level of response depends on the position of the sensors relative to the neutral axis of the tube. Results are in good agreement with a theoretical model calibrated with measurements obtained by standard deformation sensors. The bond from the sensors to the riser section did not show and degradation up to the maximum strain level (1200 microstrains). Even removing the steel straps did not cause a detachment of the sensors. On the other hand, sensors attached by clamping only did show the same response, proving that clamping or gluing alone can guarantee perfect strain transfer. Using both will therefore increase the redundancy and reliability of the system significantly.

CONCLUSIONS

The presented system is designed to monitor the static and dynamic strain of offshore risers to evaluate their performances and fatigue life. The sensors measure average strains over a measurement basis between 0.5m and 5m, typically 2 m. Through a junction box, sensor signals are transferred to a standard underwater cable. The surface equipment consists of an interferometer that allows both dynamic and static strain measurements.

Between 2002 and 2003 this system has been qualified on a riser mock-up in hyperbaric chamber (up to 360 bar) and on a full-scale riser section in controlled laboratory conditions. These results show that the sensors and all interconnection systems can be used safely at pressure of up to 300 and are therefore adapted for the monitoring of deep-water risers.

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