FIBER OPTIC PRESSURE AND TEMPERATURE SENSOR FOR DOWN-HOLE APPLICATIONS

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ABSTRACT

This paper is devoted to the description of a fiber optic sensor adapted to the permanent monitoring of oil-wells and providing a simultaneous determination of pressure and temperature in a down-hole environment. This sensor includes two interferometric transducers in a serial configuration (Fabry-Perot type for the pressure, including a deformable membrane, and birefringent type for the temperature) and uses spectral modulation encoding techniques to recover at large distances both informations without cross-talk and with a perfect down-lead insensitivity.

1. INTRODUCTION

In the Oil industry, the knowledge of the down-hole pressure on a continuous basis is a key factor for reservoir monitoring and production optimization. Up to now, the monitoring of this parameter has been based on electronic probes, whose behaviour in such adverse environment (high temperature and corrosion) can be summarized as follows :

- at low temperatures (less than 90 °C), the reliability of the electronics is satisfying, and the only working problems are sometimes induced by the cables and the connectors used between the down-hole sensor and the surface processing unit,
- at intermediate temperatures (between 90 °C and 130 °C), the electronics probes exhibit important drifts, in the range of 3 psi per month,
- at high temperature (more than 130 °C), the pressure measurement can not be achieved at this time through electronics means.

To overcome these problems, the use of passive fiber optic sensors seems to be very attractive, since the optical transduction scheme allows not only to remote all the electronics compounds inside the surface unit, but also to multiplex on a single optical fiber link both pressure and temperature informations : the value of this second parameter can be particularly used to correct the residual thermal dependence of the pressure transducer.

Since 1989, the Société Nationale ELF Aquitaine (Production), SNEA(P), and the Optics and Optoelectronics Division of BERTIN & Cie have started a close cooperation, in order to implement an industrial extrinsic fiber optic probe in accordance with the following requirements (Breadboard Phase):

- Pressure	Range	: 0 - 200 bars
	Accuracy	: .2 bars (.1% of the full scale)
	Drift	: < .4 bars/year
- Temperature	Range	: 0 - 160 °C
	Accuracy	: .5 °C (3% of the full scale)

The distance between the surface control unit and the sensor itself is about 2 to 7 kilometers, depending on the type and location of the monitored down-hole. In the next development phase (Pilote Phase, including field experimentations), the pressure and temperature ranges will extend respectively to 350 bars (5000 psi) and 200 °C.

2. GENERAL PRESENTATION OF THE CODING SCHEME

In order to achieve the accurate coding of pressure and temperature informations into an optical quantity, and to reach the down-lead insensitivity enforced by the large distance of propagation (up to 15 kilometers), as well as the possible insertion of various passive optical elements (connectors, splices, branching couplers or multiplexers) between the Probe and the Emission/Detection Unit, we have chosen to use Spectral Modulation Encoding Techniques (sometimes also called Fiber-Coupled White-Light Interferometry or Coherence Multiplexing)[1-6].

In such techniques, two unbalanced interferometers, a sensing one and a receiving one, are connected through optical fiber links and illuminated by a broadband emitter, whose coherence length is small regarding the Optical Path Difference (OPD) created by each interferometer. The variations of the physical parameter X, for which the sensor is designed, induce small variations of its OPD $\Delta_s(X)$ around a mean value $\Delta_s(0)$. If the detector creates a fixed OPD Δ_d matched to this mean value, an intensity coded interference phenomenon reappears when both interferometers are connected in a serial configuration. This encoding scheme has two main features :

- first, the usefull quantity is the phase mismatch ϕ between the probe and the receiver :

  $$\phi = \frac{2\pi}{\lambda} \{\Delta_s(X) - \Delta_d\}$$

  so that the optoelectronic processing needed by the phase extraction can be implemented in the receiving interferometer instead of the sensing one.
- secondly, an unique receiver can demodulate the phase informations associated to different sensors, or to different parameters in the same sensor. As an illustration, if the sensor includes two distinct interferometers, whose OPDs, $\Delta_1(T)$ and $\Delta_2(P)$, are respectively affected by the temperature and the pressure, and are separated by a sufficient gap in comparison with the coherence length of the emitter ($\Delta_1(T) - \Delta_2(P) >> l_c$), the receiver can be tuned on each value in parallel or successively, and can also select both informations without crosstalk.

Finally, since the phase information is coded into the spectrum of the light source, both interferometers can be connected by any kind of optical fibers, and especially by multimode type.

3. DESIGN OF THE PROBE

3.1 - DESCRIPTION OF THE PROBE

We have chosen to use a sensor including two interferometers in a serial configuration, as indicated in Figure 1. The first interferometer is a FABRY-PEROT, whose mirrors are respectively the rear face of a glass plate with partial reflective coating and the fine polished surface of a plane metallic membrane. The length of the FP cavity is defined by the thickness of a thin glass spacer, located between the glass plate and the membrane. The second interferometer is based on a birefringent quartz crystal, whose neutral axis are oriented at 45° of the direction of a dichroic polarizer P.

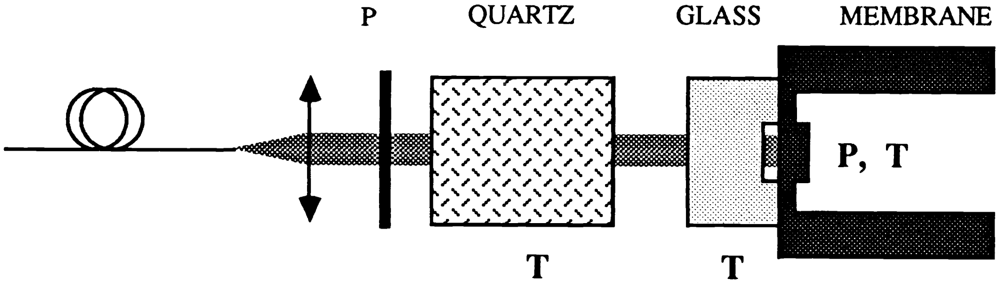

Fig. 1. Design of the Probe

The light provided by the incoherent emitter (a simple LED) is launched into the core of a multimode step index fiber. The extremity of this fiber is precisely positioned at the focal plane of a single lens, in order to obtain a well collimated optical beam. This beam is polarized with the help of the dichroic polarizer, passes through the birefringent plate, is reflected by the FABRY-PEROT and, after a new propagation inside the quartz crystal, is focussed back into the same fiber.

A pressure change induces only a deformation of the metallic membrane, and consequently a variation of the length of the FP cavity, while a temperature change induces different effects : mainly, a variation of the quartz birefringence, but also a small modification of the length of the FP cavity (the amount of this effect is driven by the thermal dilatation of the glass spacer). Moreover, the deformation of the membrane for a given pressure is affected by the temperature changes, as a result of the thermal dependence of its YOUNG Modulus (about 10% of variations in the specified 160 °C range).

By using the multiplexing ability of the encoding scheme, we can : first, determine the temperature of the probe by measuring the OPD created by the birefringent plate (thickness e)

$$\Delta_T = 2e\,\Delta n$$

and secondly, taking into account this temperature value and all the thermal effects described before, calculate the pressure from the thickness value (E) provided by the determination of the FABRY-PEROT OPD

$$\Delta_P = 2E$$

3.2 - SPECTRAL TRANSFER FUNCTION OF THE PROBE

If we consider the FABRY-PEROT interferometer as a special mirror with a complex reflectance $r(\sigma)$, the spectral transmittance of the polarimetric arrangement using unpolarized light is given by the classical formula

$$T(\sigma) = \frac{1}{4}\, r(\sigma)\, r^*(\sigma)\, \{1 + \cos 2\pi\sigma\Delta_T\}$$

By replacing the complex factor $r(\sigma)$ by the usual expression of the FABRY-PEROT reflectance (R_1 and R_2 are the reflection coefficients of each mirror)

$$r(\sigma) = \sqrt{R_1} + (1-R_1)\sqrt{R_2}\, e^{-2i\pi\sigma\Delta_P} \sum_{k=0}^{\infty} \left(\sqrt{R_1R_2}\, e^{-2i\pi\sigma\Delta_P}\right)^k$$

we obtain finally the spectral transmittance of the whole probe

$$T(\sigma) = T_0 \left[1 + \cos 2\pi\sigma\Delta_T + \sum_{k=1}^{\infty} m_k \cos 2\pi\sigma k\Delta_P + \frac{1}{2} \sum_{k=1}^{\infty} m_k \cos\{2\pi\sigma(\Delta_T \pm k\Delta_P)\} \right]$$

$$T_0 = \frac{1}{4} \left\{ \frac{R_1 + R_2 - 2R_1R_2}{1 - R_1R_2} \right\} \qquad m_k = \frac{2\,(1-R_1)\,(1-R_2)}{R_1 + R_2 - 2R_1R_2}\,(R_1R_2)^{k/2}$$

where T_0 is the mean transmittance of the serial interferometric arrangement and m_k the depth of modulation associated to the k-th harmonics of the FABRY-PEROT cavity.

In this expression, we can isolate different spectral modulation frequencies : a pure frequency Δ_T associated with the polarimetric interferometer, a set of harmonics $k\Delta_P$ created by the FABRY-PEROT arrangement and the result of the spectral beat between these both terms, that is $k\Delta_P \pm \Delta_T$.

The accurate demodulation of pressure and temperature parameters without crosstalk assumes that the gaps between all these frequencies are greater than the coherence length of the emitter, in order to avoid the least overlapping in the encoding scheme. A possible solution for this problem is provided by the following criteria :

$$\Delta_T = 2\Delta_0 \qquad \Delta_P = 3\Delta_0$$

which allows to transform the OPDs spectrum into a periodic frequency comb-filter, whose period is exactly equal to Δ_0. Naturally, the choice of this parameter should be made in accordance with the aimed ranges and sensitivities for the pressure and temperature determinations, as well as with the coherence properties of the source.

3.3 - FINAL SOLUTION

The temperature transducer finally used in this laboratory prototype of down-hole sensor is a quartz crystal, 15 millimeter thick, which provides an Optical Path Difference of 280 microns around 850 nanometers, and a thermal sensitivity in the range of 30 nm/°C. The overall OPD variation in the specified range (160°C) reachs thus 4.8 microns.

The pressure transducer is based on a INCONEL alloy membrane, whose design has been optimized with NASTRAN Code, in order to ensure an overall deformation of 5 microns under 200 bars of pressure, and to hold its central zone in a perfect flatness (better than $\lambda/8$) during this deformation. The selected concept allows also to reduce the stress distribution into the membrane at minimal level, and to remain widely inside the limit of elasticity of the metallic alloy. Moreover, the shape of the membrane in its interface zone is chosen to avoid any coupling with the deformations of the external stainless body, on which the membrane is tightly fixed.

The front mirror of the FP and the spacer are manufactured with a CORNING glass (Reference B 42 73), whose thermal properties are matched with those of the INCONEL alloy. The thickness of the spacer is equal to 210 microns, in accordance with the choice criteria presented above. The pressure sensitivity of this FP transducer is about 50 nm/bars, while its residual thermal dependence reachs 5 nm/°C.

The overall dimensions of the prototype probe, including the external stainless body, are 40 mm of diameter for 14 cm of length.

4. EXPERIMENTAL RESULTS

4.1 - EXPERIMENTAL SET-UP

A functional description of the experimental set-up is presented in Figure 2. As Emission/Detection Unit, we use the ACCORD® Module, which has been widely described in a previous paper[7]. This system is based on :

- a passive homodyne demodulation scheme to recover the phase mismatch between the sensing and receiving interferometers,

- a dual-wavelength arrangement, in order to remove the 2π ambiguity in the phase determination. The sources are standard LEDs with slightly different central wavelengths (855 nm et 831 nm) and large spectral bandwith (between 50 and 60 nm). The beat wavelength reach 30 microns, while the coherence length of both emitters do not exceed 20 microns. All these values are compatible with the range of OPDs variation (nearly 11 microns).

- two different optical detection heads, one for the pressure and one for the temperature, each optical head including basically a static interferometer, whose OPD is matched with that of the corresponding transducer.

The optical links between the probe and the receiver, as well as inside the detection unit, are standard 100/140 Step Index Multimode fibers.

The pressure and the temperature applied to the optical probe can be modified through a dedicated Test Bench, in order to simulate the down-hole environment during large period of time. The values of both parameters can be recorded with the help of classical means (thermocouple, electronic pressure transducer).

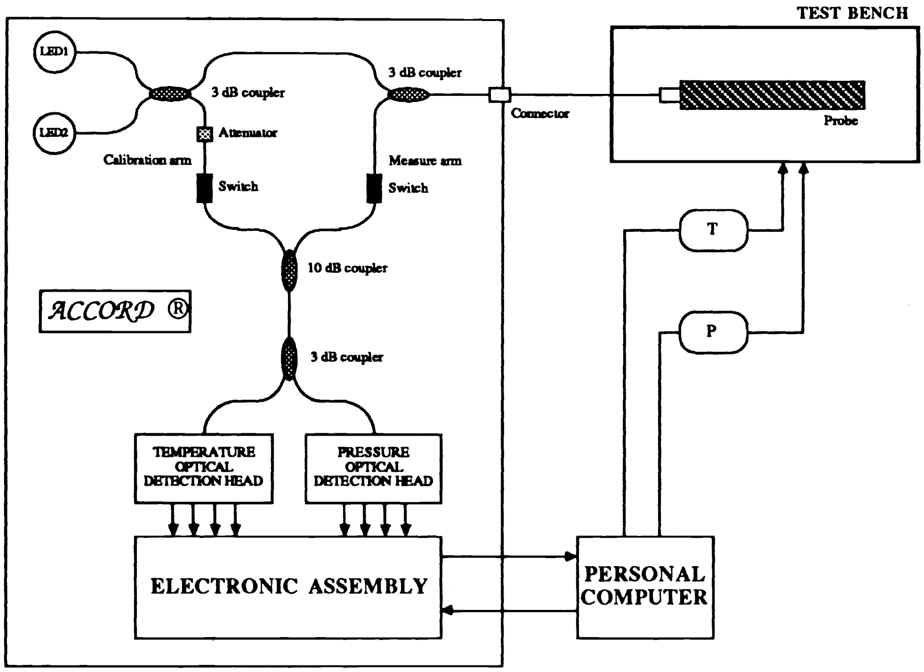

Fig. 2. Experimental set-up

4.2 - EXPERIMENTAL RESULTS

The first examples (Figures 3A and 3B) describe the response of the probe demodulated by the ACCORD® Module, when the pressure is linearly sweeped between 0 and 200 bars in laboratory conditions (without thermal regulation of the test bench). Before and after this sweep, the pressure is keep constant during short periods of time respectively at 0 and 200 bars. The time scale is expressed in quarter of seconds (1 U = 250 ms), and the total duration of the recording is about 6 minutes.

The Figure 3A shows the OPD mismatch variations recorded by the Pressure Optical Detection Head during this sweep. The linear response shape is achieved without any data processing. The measured sensitivity is about 51,4 nm/bars, in good agreement with the expected value.

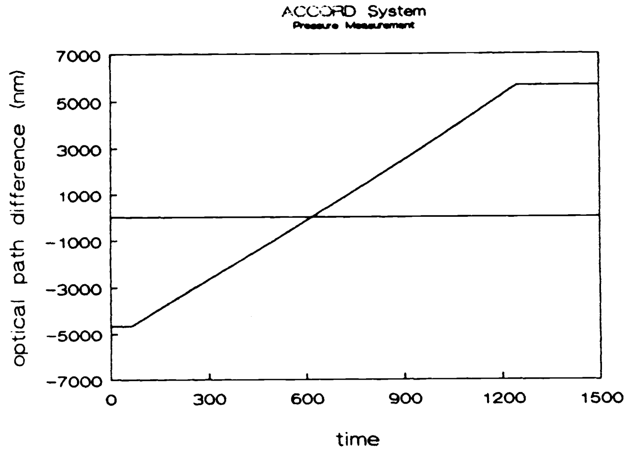

Fig. 3A. Pressure OPD Output
during a 200 bars pressure sweep

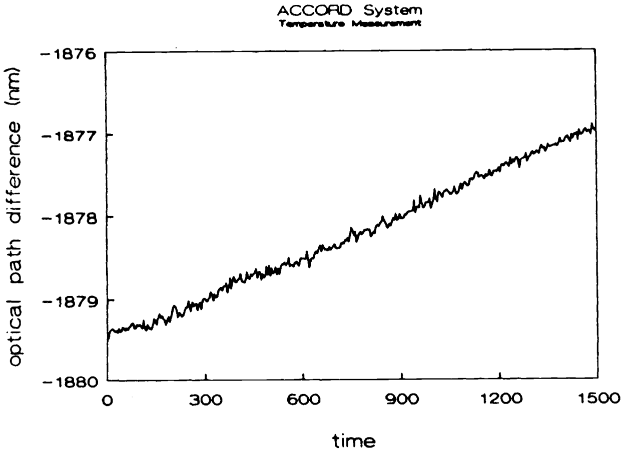

Fig. 3B. Temperature OPD Output
during a 200 bars pressure sweep

The Figure 3B shows the evolution of the OPD mismatch provided by the Temperature Optical Detection Head during the same sweep (the scale is widely extended). The quartz transducer is able to detect a small increasing of the temperature during this pressure sweep (about .08 °C), which is the standard evolution of the laboratory in which the experiment has been performed.

This first example establish that the informations provided by the Quartz transducer are not affected by the large pressure variations simultaneously applied to the probe and allows to evaluate the noise amplitude of the Detection Unit (about .1 nm).

The second example (Figure 4) describes the response of the probe demodulated by the ACCORD® Module, when the temperature is sweeped at fixed pressure between 20 and 200 °C with the help of the test bench. The measured sensitivity is about 30 nm/°C, in perfect accordance with theoretical predictions. The used time scale is expressed here in half of minutes (1U = 30 s), and the total duration of the recording is about 2 hours.

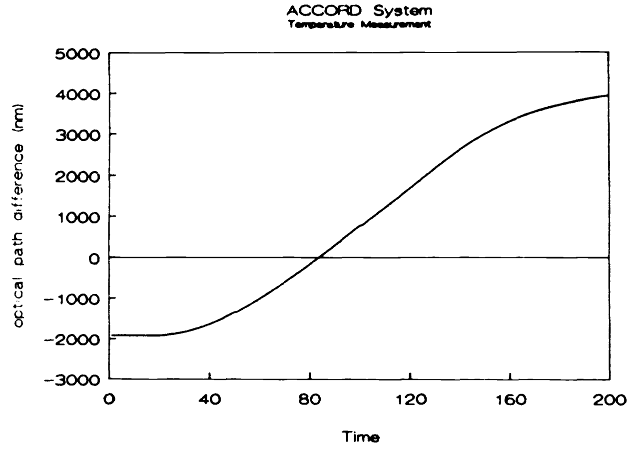

Fig. 4. Temperature OPD Output
during a 20-200 °C temperature sweep

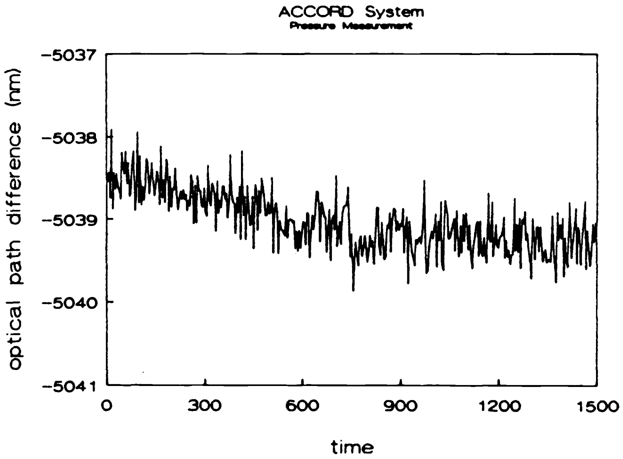

Fig. 5. Pressure OPD Output
at atmospheric conditions

The Figure 5 shows the free evolution of the Pressure OPD output at stabilized amospheric conditions, and allows to quantify the noise equivalent pressure (about 4 millibars). The small drift of the signal during the recording (.8 nm) is due to the residual thermal dependence of the FP transducer (dilatation of the glass spacer) : the corresponding temperature variation do not exceed .16 °C, which corresponds again to the evolution of the experimental room.

6. CONCLUSION

This work demonstrates the efficiency of the spectral modulation encoding techniques to recover with the same probe pressure and temperature informations in a down-hole environment. Resolution as high as 20 mbars for the pressure, and 10 mK for the temperature are reached without difficulty. The key points of such sensor is the mechanical optimization of the membrane and the implementation of two interferometric transducers into the probe in a serial configuration. Next planned steps for the development of this technique are the realization of field versions of 5000 psi probes, and the manufacturing of a ruggedized model of the emission/detection unit working at 1300 nm.

7. REFERENCES

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