Lifetime stability and reliability of fibre-optic seismic sensors for permanent reservoir monitoring

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Summary

Permanent reservoir monitoring (PRM) using seabed arrays of seismic sensors is becoming a well recognised tool for optimizing production and increasing reserves at lower cost and risk through improved reservoir management. An approach based on fully fibre-optic sensors offers significant benefits in terms of long term reliability and reduced through-life costs. A successful PRM system will also require high stability of the output seismic data in terms of sensitivity, noise and other key performance attributes throughout its operating lifetime. We discuss issues which affect system stability, and describe how we have addressed these through a combination of careful system and mechanical design based on over 25 years experience of analogous systems and rigorous qualification, demonstrating over 30 years' equivalent accelerated sensor lifetime without performance change. We present results from two field tests, 3 years apart, to show that highly stable sensor operation can be achieved in real field environments.

Introduction

The benefits of PRM systems are now becoming well known, where time-lapse data on demand allow operators to make informed reservoir management decisions in a timely manner along with field development plans. PRM systems, which can comprise arrays of in excess of five-thousand 4C sensing units laid on the seabed, are expected to operate for up to 25-years and are used to record small and subtle production-induced changes in the reservoir.

The data quality from full-azimuth broadband seabed seismic data improves accuracy and reduces model uncertainty, while permanent sensors improve repeatability and 4D detectability. For those benefits to be fully realised, the system needs to produce reliable data over an operating life that could last two or three decades. The question of reliability (that is, maximising the number of operating channels throughout the system lifetime) has been addressed previously (Nash, Strudley, 2010). In addition to reliability, sensor stability (that is, the ability of the system to record seismic data which is stable in sensitivity and other performance attributes throughout its lifetime) is also a vital attribute for a successful PRM system.

Here we discuss how to maximise both the reliability and the performance stability of a PRM system based on fully fibre-optic sensors. We describe good design practice in terms of sensors and other system aspects, and we describe the use of accelerated temperature lifetime methods to prove sensor stability. We explain how military heritage, qualification and twelve field tests have been part of the rigorous development programme, before we finally use results of two recent field tests of a PRM cable, 3-years apart, to show that excellent levels of performance stability can be achieved in real environments.

Fully fibre-optic PRM

PRM systems based on fully fibre-optic sensor technology have been one of the major developments in recent years. The benefits of fibre-optic systems for PRM include the removal of underwater electronics and electrical power requirements, leading to an increase in system lifetime and a reduced chance of water-induced failure. We have developed such a system, based on the Stingray technology, which also utilises a powerful optical multiplexing architecture to minimise connector and component count in the subsea arrays (Nash, Strudley, 2008). This technology allows in excess of 250 sensor channels to be multiplexed onto one pair of optical fibres. This technology has also undergone rigorous qualification to ensure its survivability, operation and reliability in water depths up to 3,000m.

However, fibre-optic sensors which are mechanically simple, have few moving parts and use inert materials provide the best potential for high sensor stability over long periods of time. In this case the stability is measured in terms of: sensitivity; seismic frequency response; noise floor; and all other critical performance parameters remaining within their specified limits over the

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design life of the system. The stability is accentuated by the fact that the sensor itself is completely passive, and the active signals used to extract information from the sensor are generated elsewhere (typically in an acquisition and recording unit located at the surface). Factors such as the system noise are essentially determined at the recording unit rather than at the sensor, so any changes in such factors can be measured and addressed much more easily than changes in the sensor. This stability needs to be maximised by careful mechanical design both of the sensors and of their housings, and confirmed by appropriate qualification.

We have developed accelerometers and hydrophones based on a common optical and mechanical approach. In both cases, the sensing element is 40m of optical fibre wound onto a simple mandrel. In the accelerometer, the mandrel is mechanically designed so that it applies force to the fibre coil which is directly proportional to axial acceleration, and in the hydrophone it is designed to apply force which is directly proportional to the surrounding pressure field. In both cases the force applied causes a change in the length of the optical fibre which can be measured as a phase change in light passing through the coil.

To prove the sensor stability with time we carry out accelerated lifetime testing, which involves exposing the sensor to extended periods at a temperature significantly higher than its normal operating temperature. In line with recognised material ageing rules, we expose our sensors to temperatures of 50 degrees C, according to the principle that 1 month at 50 degrees C is equivalent to 2 years at 5 degrees C (a typical seabed temperature). We then measure the key performance attributes of our sensors at regular intervals. Figure 1, shows the frequency response (up to 400 Hz) of a hydrophone which has been subjected to the equivalent of 30-years at 5 degrees C (15 months at 50 degrees C). The sensor frequency response remains flat and the sensitivity has varied by less than 1dB (within measurement limits) over that period (similar results are also achieved by the accelerometer).

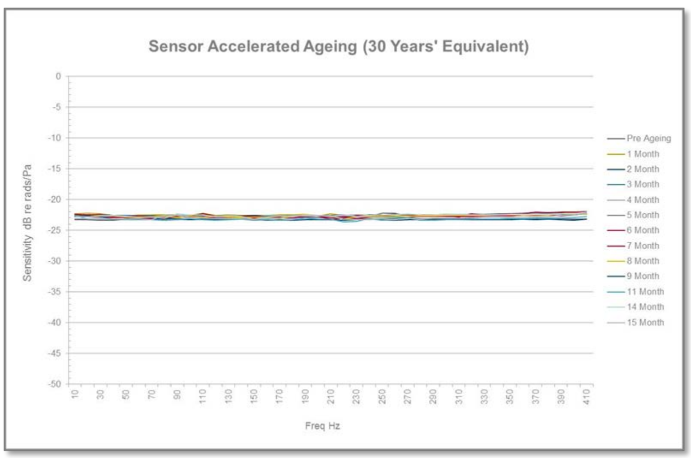

Figure 1: Hydrophone stability over 30 years

Figure 2: Optical sensor housing

Sensor housing stability

While the long term stability of our sensors has been proven, this stability must be maintained by careful design of the sensor housings, as this is a potential cause of stability issues in field environments. General design principles which should be followed include:

- Minimising the mechanical complexity of the housing
- Ensuring that sensors are directly coupled to the relevant sensing medium, but minimise coupling to other potential sensor media
- Ensuring that potential for corrosion and other long-term material changes is minimised

In following these design principles, we have taken the following steps:

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- The accelerometers are rigidly mounted in a strong cylindrical pressure housing maintained internally at atmospheric pressure, which couples the sensors directly to the seabed and the local acceleration field, but isolates them from static or dynamic pressure changes
- The hydrophone is mounted outside the pressure housing, within an acoustically transparent polyurethane which couples directly to the surrounding pressure field
- No metal is exposed to seawater, so potential for corrosion is minimised

This design, shown in Figure 2, has been qualified via a series of tests which have included accelerated vibration ageing (i.e. exposure to over 2 million cycles of shock, equivalent to the total number of seismic shocks likely to be seen by a sensor in its lifetime), followed by retesting to show that performance levels are maintained.

Field tests

Final proof of full system stability is best achieved from repeated field tests. We have completed 12 field tests on our system covering a period of over 7 years, culminating in 2 field tests at the Tjeldbergodden site in Norway.

The scope of the field trials at the Tjeldbergodden site included the installation of 12 receiver stations, 4C fibre-optic seismic cable and data acquisition. The first field trial was conducted November 2008 and a repeat test was conducted in December 2011. The main objective of this test was to investigate if all channels from the sea floor receiver stations were working satisfactorily and that the system response remains stable and repeatable three years after deployment at the site. The repeatability analysis and performance will of course imply that the whole system is assumed to respond in a repeatable fashion, which includes the installed sea floor fibre-optic receivers, the top-side instrumentation (interrogator) and the seismic source used. However, since different seismic sources were used in 2008 and 2011, the recorded data naturally exhibited some inherent differences which had to be accounted for when analysing the data. During the test in 2008, a 1960 cu.in. G.GUN source array towed at 6m depth was utilised during the main shooting programme, and in 2011 a 2006 cu.in. BOLT source array was used. The two arrays, with the different volumes and number of guns used in each array made the signatures quite different when it came to output strength. A comparison of the hydrophone output signatures is shown in Figure 3.

Key issues addressed in the data analysis were visual inspection of raw data plots, vector fidelity, and frequency response, intrinsic system generated noise, signal-to-noise ratio and ground-station coupling. An example of hydrophone common receiver gathers (CRGs) from all twelve stations, using full source of 2006 cu.in., is shown in Figure 4. Repeat spectra from 2008 and 2011 are shown in Figure 5. Hodograms in Figure 6 both show that the vector fidelity and repeatability is very good between 2008 and 2011.

Conclusions

We have discussed the importance of system stability for the benefits of PRM investments to be fully realised. We show how careful mechanical design of both sensors and sensor housing followed by a rigorous qualification programme is key for the technology to produce reliable and stable data throughout its operating lifetime. Finally we have shown field results confirming stable and repeatable data from a permanently installed 4C fibre-optic sensor cable.

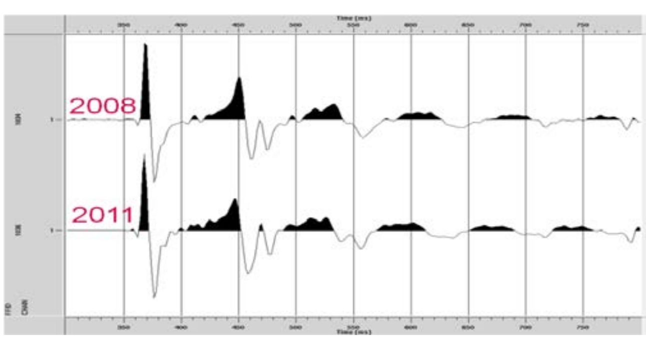

Figure 3: Hydrophone measurements from a selected receiver station from 2008 (upper) and 2011 (lower). The shots are from the closest offsets of a 100 cu. inch gun

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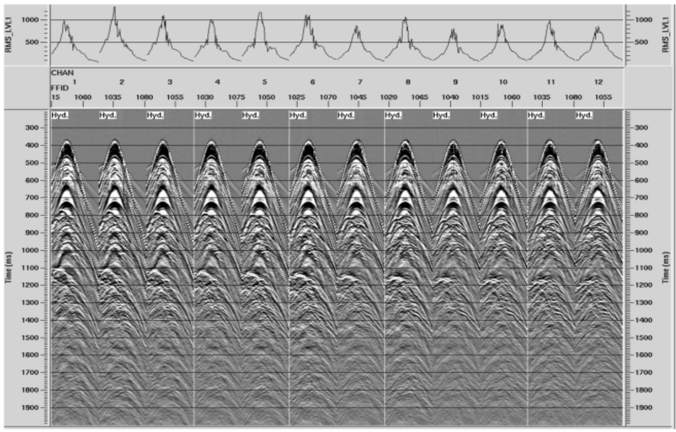

Figure 4: Hydrophone CRGs of 2006 cu.in. source array of all receiver stations from 2011

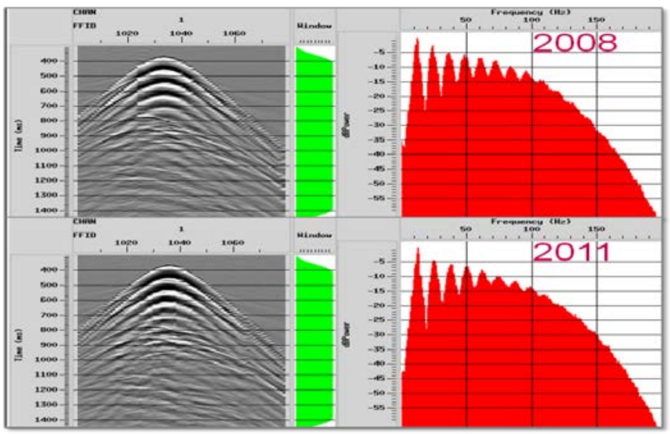

Figure 5: Repeat spectra of a selected hydrophone CRGs from 2008 and 2011

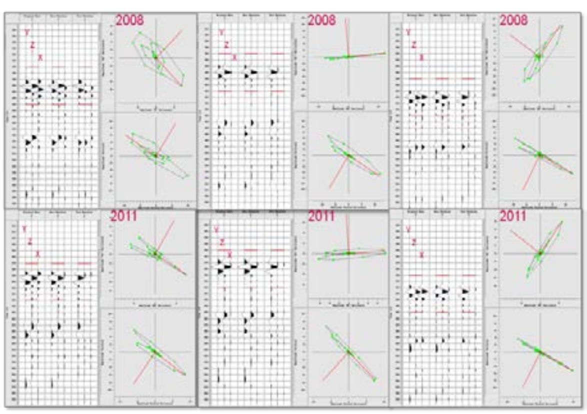

Figure 6: Hodograms from a selected receiver station with input from 3 shots. Panels at left and right show shots at about 150m to each side of the receiver station and at around zero offset (middle panel)

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EDITED REFERENCES

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REFERENCES

Nash P., A. Strudley, 2008, Optimum optical architectures for seismic reservoir monitoring: Offshore Technology Conference, OTC-19678-PP

Nash P., A. Strudley, 2010, High reliability fibre-optic sensor architectures for seismic permanent reservoir monitoring: 72nd Conference and Exhibition, EAGE.

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