Perturbations in 4D marine seismic

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SUMMARY

A new concept for acquiring calibrated towed streamer seismic data is introduced through a new acquisition and processing system. The specification of the new system has been defined by rigorous analysis of the factors that limit the sensitivity of seismic data in 4D studies and imaging. New sensor and streamer technology, new source technology and advances in positioning techniques and data processing have addressed these limitations.

Sensitivity analysis revealed that the most significant perturbations to the seismic signal are swell noise and sensor sensitivity variations. Conventional analog groups of hydrophones are designed to suppress swell noise however a new technique for data-adaptive coherent noise attenuation delivers even greater noise suppression for densely spatially sampled single-sensor data.
Although modern source controllers provide accurate airgun firing control the signature of an airgun array may vary from shot to shot. This can be due to factors such as changes in the array geometry, air pressure variations, depth variations and wave action. A method for estimating the far-field signature of a source array is the Notional Source Method (proprietary to Schlumberger) which has been steadily refined since its first disclosure. A recent development compensates for variation in source array geometry by monitoring the position and azimuth of each subarray using GPS receivers mounted on the floats.

New calibrated positioning and streamer control systems are part of the new acquisition system. Active vertical and lateral streamer control is achieved using steerable birds and positioning uncertainty is reduced through an in-built fully braced acoustic ranging system.
Calibrated marine seismic data are achieved through quantifying the source output, the sensor responses and positioning uncertainty. The consequential improvements in seismic fidelity result in better imaging and more reliable 4D analysis.

Keywords: Calibrated seismic data, perturbations, Q-Marine, 4D seismic, single sensor recording, Notional Source Method, steerable streamers.

INTRODUCTION

Reservoir monitoring using time lapse or 4D seismic has demonstrated its effectiveness for understanding the dynamic behaviour of the reservoir and its value for reservoir management. 4D seismic studies can:

- Map fluid movements, pore fluid saturation changes and pressure changes
- Identify unswept oil and infill drilling opportunities
- Identify flow units and flow barriers
- Monitor the performance of enhanced recovery programs
- Quantify and constrain the spatial properties of the reservoir model

Most time lapse survey interpretations have been made for reservoirs with highly porous sands where fluid replacement has the greatest effect on seismic response. The largest time lapse signals are induced by the replacement of either oil or water by gas, the replacement of oil by water generally leads to a smaller time lapse signal. Altering the pressure regime within a reservoir will induce time lapse anomalies within the data and the period between surveys will also affect the magnitude of the time lapse signal.

The method has a yet unrealized potential that will open for wider use if higher repeatability and greater sensitivity can be obtained. Wider applications could be more quantitative interpretations, monitoring over shorter time intervals and application of the technology to smaller, tighter and more complex reservoirs. However the time lapse signal, like all signals, is only detectable if it is not masked by noise. Perturbations (errors and differences) between different phases of a 4D seismic study create noise when datasets acquired at different times are analysed for changes. This noise can mask the subtle variations in the seismic response of the reservoir that indicate changes in pore fluids. The sources of the perturbations can be internal or external to the acquisition system. Examples of internal perturbations are hydrophone calibration variations and positioning errors. External perturbations include environmental effects such as rough sea and tidal variations. We can divide the perturbations (internal and external) into:

- Those that affect the received signal such as sensor sensitivity variations and ambient noise like swell.
- Those that affect the emitted source signature such as shot-to-shot variations in the source output and the array directivity.
- Those that affect positioning accuracy and reliability such as sea currents and positioning network.

The effects of these perturbations have been studied using both modelled and real data examples and the impact on seismic data quality quantified. It was with these factors in mind that Schlumberger developed a new marine acquisition system called Q-Marine. The design features of system that differentiate it from 'conventional' marine acquisition systems may be summarised as follows:

- Calibrated sensors individually recorded
- Calibrated positioning with streamer steering capability
- Calibrated sources

These features are intended to address the sources of perturbation that impact the quality of seismic data both for high resolution imaging and repeatability in 4D studies.

CONTROL OF PERTURBATIONS

Calibrated receivers

The two most significant perturbations to the signal received by a towed streamer are swell noise and sensor sensitivity. Conventional streamers contain hard-wired spatial arrays of hydrophones designed to suppress noise, these arrays also act as a spatial filter for non-vertical seismic ray paths. Connecting the outputs of individual receiver elements forms receiver groups, however there are drawbacks associated with the nature of the analog array. The outputs of these elements are simply summed without any processing applied, as the group forming is hard-wired in the acquisition system. The ideal would be to record each individual receiver element into its own seismic channel (single sensor recording) so that a dense grid of receivers samples the wavefield alias free, however, this has been prohibited by cost and equipment limitations. The Q-Marine system is able to record data from each single sensor in the streamer and can record more than 4,000 individual hydrophones on each of up to 20 streamers giving a total of up to 80,000 channels. Onboard computer processing systems perform sophisticated noise attenuation much more effectively than hard-wired arrays, while preserving signal amplitude. The processing system compensates for individual hydrophone sensitivity variations and dropouts. New proprietary high fidelity tubular hydrophones are used each delivered with its own aging profile and sensitivity certificate. These values are stored in the streamer electronics for automatic data calibration.

Recording individual sensors allows more effective removal of noise caused by the movement of the equipment through the water. The principal noise source affecting marine towed streamer data is the flow of water across the streamer. Vertical cross-flow can be introduced by wave action and is often termed swell noise. Horizontal cross-flow is introduced by the towing of the equipment and local water currents. All sources of cross-flow generates vibrations in the streamer in a number of characteristic modes, appearing completely chaotic and impossible to handle in data from conventional streamer groups due to inadequate spatial sampling. The same noise will, however, from single sensor records appear coherent and removable utilizing adaptive noise attenuation methods.

A new technique for data adaptive coherent noise attenuation has been developed (Özbek, 2000) which delivers greater noise suppression for densely sampled point receiver data than conventional arrays. The method works by searching for coherent low frequency, low velocity noise fields across groups of adjacent traces. A suitable multi-channel filter is then defined to attenuate the noise while leaving the reflected signal. The result is a significant improvement of the signal-to-noise ratio (in the region of 6-12dB) of the seismic data, and increased robustness against noise during data acquisition in marginal weather (see Figure 1).

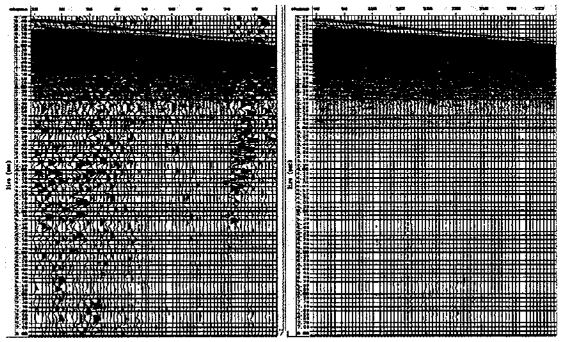

Figure 1. Comparison of shot domain data recorded simultaneously on conventional analog group-forming streamer (Nessie 4 left) and a point-receiver streamer (right). The point-receiver data are displayed after digital group forming using the data adaptive coherent noise filter.

Calibrated positioning

Repeatability of the acquisition footprint is regarded as the key requirement for 4D surveys. Some of the most successful 4D studies have been those conducted using the same acquisition configurations between successive surveys. This means identical streamer lengths, separations and depths. The source arrays should be identical with the same tow depths, sailines should have identical directions and shot locations to those of the baseline survey. With a conventional towed streamer system it is very difficult to exactly replicate receiver positions due to the effects of current on streamer feathering.

Variations in the acquisition footprint from survey to survey also depend on positioning accuracies. Relative positioning accuracies across a spread depend on a combination of GPS nodes, acoustic range-finders and compasses and the performance of a network solver. Crossline accuracies are poorer than inline and conventional systems have crossline errors which may be as high as 12m. Archer et al. (1999) studied the effects of positioning errors and Morice et al. (2000) analysed the impact on 3D imaging as functions of dip and frequency. In broad terms they suggest a target accuracy of 2-3m is required to reduce non-repeatable noise in a 4D signal below other sources of error.

The new system provides lateral steering of the streamers in addition to depth control. Utilising this, it is now possible to steer several degrees laterally from the natural streamer feather angle. This ability is coupled with a new positioning system based on a fully braced acoustic network from the front to the tail of the streamers, providing greatly improved relative and absolute accuracy. Using the new steering system, streamers can be towed with crossline separations as little as 25 m.

Streamer steering devices are mounted inline with the streamer to avoid noise and provide the desired mix of horizontal and vertical force with their two independently operating wings (see Figure 2). The ability to steer horizontally provides close and constant streamer separation giving improved crossline sampling and the ability to steer for optimal sub-surface coverage and repeatability from survey to survey.

Figure 2. Inline steerable bird. The two wings operate independently to allow vertical and lateral steering. Tests show that these devices generate less noise than conventional depth control birds

The new accurate positioning system provides a full streamer acoustic network, independent of streamer length. The acoustic positioning sources generate a robust broadband signal with each acoustic source having its own signal code enabling simultaneous shooting. The positioning signal can be received by any seismic hydrophone in the streamer and a super fast acoustic network solver performs correlation and range calculations. The result is an absolute positioning accuracy better than 3 meters anywhere along the streamers.

Streamer steering and accurate positioning improves the safety of seismic operation in busy oil fields as the streamers can be steered around potential hazards such as surface installations.

Calibrated sources

The signature of an airgun source array is known to vary from one shot to the next depending on variations in the individual airgun firing times, airgun chamber pressure, sea conditions and array geometry. These shot-to-shot variations reduce the accuracy and resolution of the seismic data, and can mask subtle effects due to reservoir pore fluid changes in time-lapse studies. Figure 3 shows how modelled changes in fluid contract can be masked by source and receiver variations.

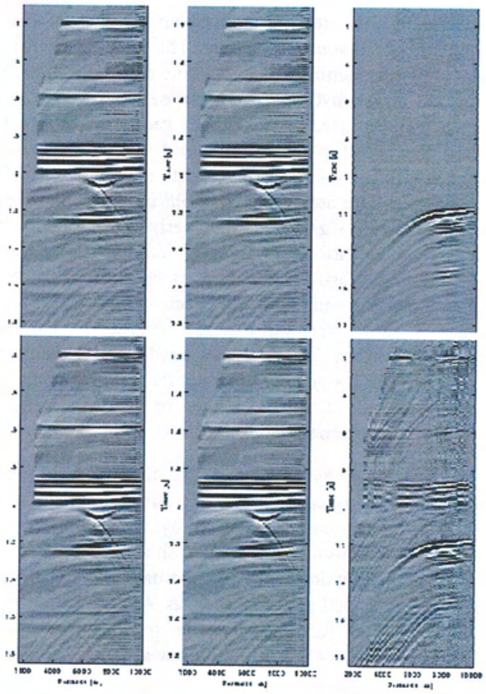

Figure 3. The upper three plots show modelled data with a 5m change in the oil/water contact, the time lapse change (right) is as much as 25dB lower than the seismic response of the reservoir. The lower three plots illustrate how the 'noise behind the signal' from random shot amplitude variations and random receiver sensitivity variations can mask the seismic differences. The variations are 5% in each case - realistic ranges for conventional technology

Removal of these shot-to-shot variations may be accomplished by signature deconvolution for which the far-field signature is required. This is the signal that would be recorded by a hydrophone placed directly below the source array. The distance from the source array needs to be sufficient such that the array output appears to the hydrophone as a single pulse rather than a number of pulses from the individual airguns. Since this distance is in excess of 100m it is impractical to record the far-field signature during production.

The far-field signature can be estimated from the combination of array components. One approach is to use a static gun signature from a library of previously recorded gun signatures and combine these using special source modelling software to calculate a far-field signature. The downside of this method is that the estimate does not include shot to shot variations caused by timing, air pressure changes and varying depths etc.

A better approach is to use a real signature for a gun recorded during the shot, this is recorded by a near field hydrophone (NFH) which is placed directly next to each gun. However each NFH not only receives the acoustic pulse from its own gun but also its ghost arrival bounced off the sea surface, signals from all other guns in the array and their ghost elements. Thus the NFH is not a pure measure of the gun signature. The new system takes the recorded NFH signals and computes an 'uncontaminated' near field signature in real time. This is done using the Notional Source Method of Ziolowski et al. (1982) which takes into account the various pressure wavefields and the relative movement of the bubbles to generate a notional source signature. The notional sources are calculated by subtracting scaled and time delayed signatures of the adjacent airgun hydrophones from each respective airgun reference hydrophone. The source geometry is used to calculate the travel path distance and time delays of the adjacent interfering energy and accurate measurements of the source geometry are derived from dGPS units on the subarray floats. The far-field signature is then derived from the notional source signatures, raw NFH signals, notional source signals and the computed far-field signature estimate are recorded on auxiliary channels on tape for each shot. The far-field signature is then used for accurate source deconvolution during processing. A further refinement is that by combining the notional source signatures offline, far-field estimates with operator selected azimuth, angle or surface reflection coefficients can be generated.

Experiments using a hydrophone towed deep below the source showed excellent agreement between the measured far-field signal and the estimate arrived at by the notional source algorithm. Compensation for the shot-to-shot variations improves the bandwidth of the seismic data and enhances the accuracy of advanced analysis such as AVO. Measurement and compensation for variations in the source signature between phases of a 4D study removes a major perturbation from the time-lapse signal.

CONCLUSIONS

Data recorded with the new generation of acquisition system will minimise the impact of the acquisition footprint on time lapse interpretations. The amount of ambient noise in the data will be greatly reduced through the use of single sensor recording and digital group forming. The quality of the final image and frequency content of data will be and the accuracy of interpretations will improve to allow the detection of weaker time-lapse signals. This will allow periods between monitoring surveys to be reduced giving greater control of the reservoir management.

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