Broadband and High Performance Vibroseis for high-density wide-azimuth land acquisition

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SUMMARY

With the advent of high-channel count recording systems, one of the major hurdles for increasing spatial sampling density has been overcome. We are able to deploy dense receiver geometries with small group intervals and compact arrays or even point receivers. This allows us to record unaliased signal and noise and therefore do a much better job with noise attenuation during processing. We can then reap the full benefits of long offsets and wide azimuths for processing, imaging and reservoir. There is a need to match the increase in receiver density on the source side. To accomplish this in 3D land seismic we need a significant increase in source productivity while decreasing the source array size.
Such productivity improvements can be created by spending less time per source point and by utilizing alternative source methodologies such as slip-sweep and blended acquisition.
The following challenge to deliver a clearer image and improved reservoir characterization is to emit and record broadband signals which offer better penetration and resolution. Our solution is to “performance-tune” the sweep to the vibrator’s mechanical and hydraulic limits. It extends bandwidth for a desired target output spectrum where low frequencies are enhanced, mid frequencies are unaffected and high frequencies retained or extended.
In this presentation, we describe our successive technological leaps towards point source-point receiver seismic acquisition and illustrate it with recording and processing case studies from different regions of the world.
Key words: broadband, high-density wide azimuth land acquisition, high-channel count recording systems, slip-sweep, blended acquisition.

INTRODUCTION

The improvement in subsurface imaging and resolution (temporal and spatial) associated with improved spatial sampling has been reported by a number of authors including Egan et al. (2009), Henley et al. (2009), Long (2004), Meunier et al. (2008) and Lansley et al. (2002). The referenced papers, and many others, provide good data examples of how improved spatial and temporal resolution and signal-to-noise ratio can result from improved spatial sampling. Improved sampling can help to facilitate reservoir characterization, identification of small-scale faulting, and the unravelling of complex geology.
Improved spatial sampling can be achieved through increased receiver and/or source density and can be cost-effectively implemented using reduced array sizes. State-of-the art seismic recording systems allow for active channel counts well above 20,000 (Seeni et al. 2010). Small receiver arrays using 3-6 geophones per group or even single sensors allow high productivity in deploying receiver equipment. For vibrator acquisition, source productivity needs to correspondingly increase. Such productivity improvements can be created by spending less time per source point and by utilizing alternative source methodologies such as slip-sweep (Rozemond, 1996) and simultaneous acquisition (Bouska et al. 2008, Howe et al. 2008, Pecholcs et al. 2010).
Improved resolution can be achieved by performance-tuning the sweep to the vibrator’s mechanical and hydraulic limits. It extends bandwidth for a desired target output spectrum where low frequencies are enhanced, mid frequencies are unaffected and high frequencies retained or extended.
This paper will focus on improving source productivity by utilizing alternative source methodologies such as slip-sweep and blended acquisition and improving resolution through the emission and recording of broadband signal. We will review various issues associated with the use of both high-productivity and broadband sources and present data examples to support our conclusions.

METHOD AND RESULTS

Reducing cycle-time with High Productivity Vibroseis Acquisition

The introduction of slip-sweep acquisition by PDO created an opportunity to improve vibroseis source effort. Slip-sweep acquisition is simply described as starting to sweep at the next VP (vibroseis source point) before the sweep has finished at the current VP. This decreases the cycletime for recording a shot and increases production rates. However, the shorter the slip-time (waiting time from the start of one sweep to the start of the next), the greater the chance of contamination by harmonic noise.
As a consequence, we looked at refining the technique to optimize productivity and developed High Productivity Vibroseis Acquisition (HPVA, Meunier and Bianchi, 2002).
HPVA is a patented deterministic noise attenuation technique which principally uses ground force measurements to remove the harmonic noise created by using short slip times. Its utilization allows multiple fleets of vibrators to operate with

short slip times without compromising data quality. As a result, our crews, in single-sweep operations, achieved production rates of over 300 VP/hr while typical flip-flop production rates were only 150 VP/hr.

The conversion of a project from a conventional design to one utilizing the HPVA technique involves the evaluation of a number of parameters to optimize both productivity and data quality. Source effort, source-to-receiver ratios, target depths, slip times and desired signal-to-noise levels all play a key role in determining the final design. The manipulation of these parameters can provide a variety of options for the client. Improved image quality, a reduction in acquisition cost, and/or reduced project cycle time are all possible benefits.

Single vibrator solution

Slip-sweep and HPVA demonstrate how vibroseis acquisition can be made more efficient. The next step to consider is reducing the source array size, so we reduced the fleet to a single unit and introduced V1 single vibrator acquisition (Meunier et al., 2007).

V1 acquisition comprises a larger number of smaller fleets of vibrators covering a dense grid of shotpoints and provides the next step-change in source productivity. Production rates of 600VP/hr have been recorded on our crews in the Middle East, opening the way to high-density wide azimuth acquisition. This brings the benefit of improved image quality via better illumination, better multiple suppression and better azimuthal amplitude and velocity information. When implementing V1, source power and signal amplitude can be compensated by increasing the sweep length of the single vibrator and by increasing the density of the shot points.

A new concept in vibrator fleet management was also introduced providing a robust and efficient operation. The vibrators are now automatically allocated slots in a GPS clock-synchronized shooting schedule and move independently on their designated shot lines. If a vibrator falls behind and misses its slot, it waits for the next available slot. At any given time in a nominal 12-vibrator schedule, up to eight vibrators are sweeping concurrently while four are moving to the next shot points and preparing to sweep.

HPVA and V1 technologies are important vehicles for improving the spatial sampling of 3D surveys for enhanced subsurface imaging and resolution in a cost-effective manner. A number of authors including Egan et al (2008), Long (2004) and Meunier et al (2008) provide both theoretical and real data support for improved imaging. In addition, many papers make the case that point source/point receiver acquisition provides decided benefits.

Data examples

Figure 1 illustrates HPVA noise attenuation applied to continuous records from V1 acquisition where the short slip times result in harmonic noise. It shows the effectiveness of HPVA method in maintaining good data quality while allowing large increases in source productivity. A comparison of the resulting images from a V1 field trial is shown in Figure 2. The schematic acquisition geometry with shot line and shot point spacing is shown for each case. Using the same bin size and the same rudimentary processing sequence for both datasets, there is a marked improvement in the coherency and resolution of the V1 image when compared to the production result. The shallow image benefits especially for the increased shot-point density, with a much stronger signal content and more coherent shallow events. The faults in the middle of the section are sharper and better defined, and the events are more coherent. In the deeper section there are also improvements in resolution and signal-to-noise ratio providing a clearer image. Further improvement can be expected by optimizing the processing for the high-density data.

Figure 3 provides an example of the reduced acquisition footprint achievable through denser spatial sampling (Bianchi et al., 2009). Further to this, Sambell et al. (2009) describes the incredible improvement in image quality that can result from multiplying conventional trace density by a factor of nearly 100 by using a cost-effective high performance vibroseis "super-crew".

Low frequency generation using seismic vibrators

The emission and recording of low-frequency energy with the Vibroseis method is cumbersome for a variety of reasons. The vibrator displacement limit, in combination with hydraulic pump flow limitations, constrains vibrator output at low frequencies (Bagaini, 2008, Sallas, 2010). Vibrator control electronics can experience difficulties in maintaining amplitude- and phase lock for low-frequency, low-amplitude sweep signals. Hydraulic nonlinearities, vehicle isolation, baseplate flexure and rocking resonance have the potential to further compromise the low-frequency output.

In Figure 4, at very low frequencies, the main constraint on the signal is the mass displacement, the parabolic red curve. At between about 4 to 10 Hz, the hydraulic fluid flow (light blue curve) becomes more important. Beyond these limits the vibrator will not be able to deliver the desired signal and significant distortion will occur. Normal vibroseis sweeps are linear, that is they sweep smoothly through the frequency band, but at low frequencies apply a taper to build up the force gradually and avoid distortion. In the linear sweep shown here in dark blue, starting at 5Hz, the limit of flow constraint is reached around 7Hz, when the drive level of the vibrator is at 75% of the maximum possible. This constrains the maximum force and hence signal strength that is applied to the ground.

Our solution (EmphaSeis) uses a non-linear sweep that is designed to fit within the various constraints as shown by the green line on the graph. As well as allowing generation of lower frequencies than a linear sweep, the flow limitation can be followed until a higher force is achieved, typically at about 90% of the maximum (black dashed line indicating the hold-down force limit). One consequence of the non-linear sweep is that more time is required to generate the low frequencies – to allow the reaction mass and fluid flow to work smoothly without distortion. This can be compensated by using a increased drive level through the mid-to-high frequencies which means this part of the sweep can progress faster and reduce the overall sweep time accordingly.

Data examples

Low-frequency Vibroseis tests were performed in the USA, Australia and Tunisia and the technique has been used in production in Egypt and Oman. In Figure 5, an additional 15dB of signal were recorded in a borehole when using a non-linear sweep of 2-80Hz, compared to a linear sweep of 5-80Hz (Baeten et al. 2010). In a test on a 2D seismic reflection line conducted in Egypt, Figure 6 shows the improved signal to noise ratio and continuity of events after migration at low frequencies. Note that in this example the EmphaSeis sweep was the same length as the conventional sweep, so the additional low frequencies were gained at no penalty to production rates. In another 2D test in Australia, what is interesting in Figure 7 is that we have not only more low frequencies, but we seem to have a slight improvement in the high frequencies also. For the very shallow target, results are very similar, however.

Although the improvement is subtle, these low frequencies could be crucial for delineating new exploration or development targets.

CONCLUSIONS

A variety of vibroseis techniques have been introduced in the last decade which has seen large gains in productivity. These gains, along with the increases in recording channel capacities have enabled large, cost-effective high-density wide-azimuth surveys to be completed.

We have shown that refinements in harmonic noise reduction have made it possible to take full benefit of the possibilities of the slip-sweep technique. This has been applied to single vibrator acquisition which can make a dense grid of single vibrator shot points compare economically with conventional vibrator arrays and yet deliver better data quality thanks to improved wavefield sampling.

Separately we have also seen the development of broadband vibroseis sweeps which can be used with existing vibrator fleets. An additional 1 or 2 octaves of low frequency signal (down to 2 Hz) can add important information for deep imaging and reservoir characterisation,

High-performance, high-density wide-azimuth broadband acquisition delivers data more suitable for high-resolution imaging and reservoir characterization.

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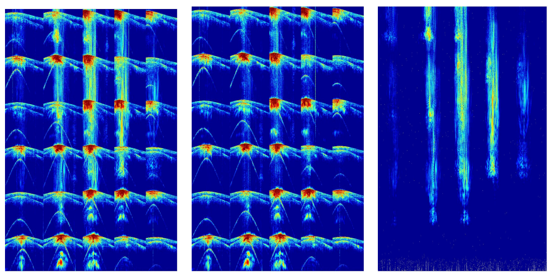


Figure 1. The short slip times and long sweep lengths result in the contamination of the record with harmonic noise (left). The harmonic noise is removed from the record (center) by subtracting a deterministic model of the noise (right).

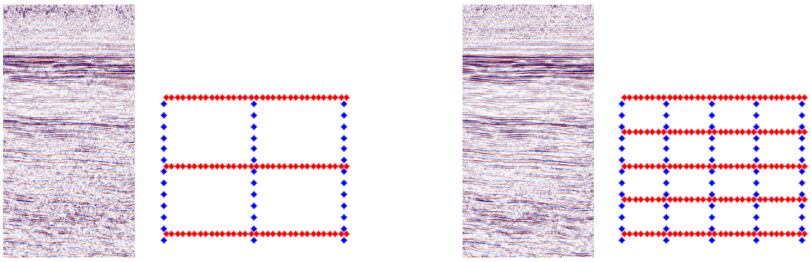


Figure 2. Comparison of the slip-sweep production data using three fleets of four vibrators (left) with the V1 single vibrator data using 12 fleets of one vibrator and the same receiver spread (right). Schematic acquisition geometry is shown below with the shot points in red. The V1 dataset has two times the shot point density and results in a superior image.

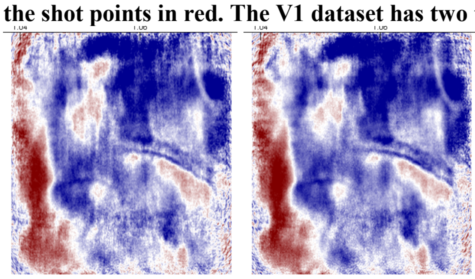
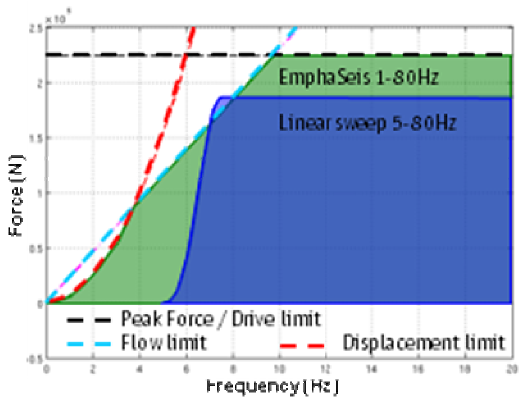


Figure 3. Comparison of slip-sweep production data using 4 x 3 vibrators with a shot spacing of 25m x 300m (left) and V1 single-vibrator data using 12 x 1 vibrator geometry and the same receiver spread. The shot spacing was 25m x 150m giving the V1 dataset twice the shot density. There is a significant reduction in the acquisition footprint resulting in a cleaner timeslice (800ms).



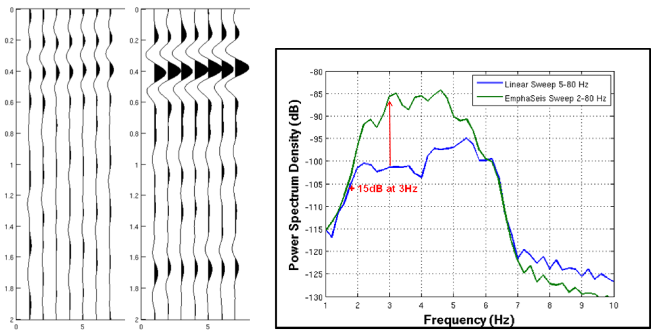


Figure 4. Schematic response curves of a seismic vibrator showing the constraints on the generated force at the low frequency end of the sweep. Figure 5. Borehole and surface data show that more energy is penetrating in the low frequencies with the EmphaSeis sweep.

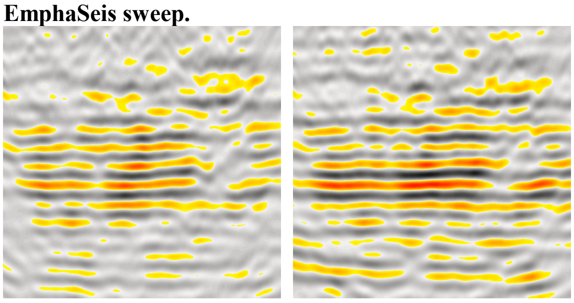


Figure 6. Conventional linear sweep (left, 18s, 6-72Hz) vs. EmphaSeis sweep (right, 18s, 4-72Hz). PSTM stacks from 0.3 to 3s with a 3-7Hz filter applied.

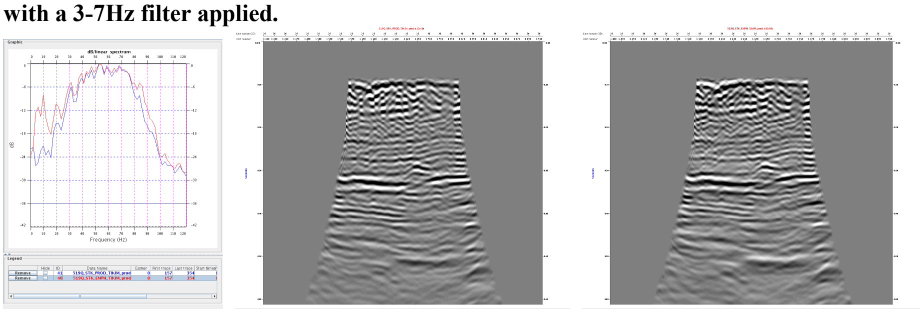


Figure 7. Linear sweep (left, 10s, 6-100Hz) vs. EmphaSeis sweep (right, 10s, 4-100Hz). PSTM stacks from 0 to 0.6s.