Numerical modelling of pseudo-random land seismic sources

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SUMMARY

Environmental, logistical and security considerations mean that non-explosive, surface seismic sources must assume increasing future importance. The challenge is to make such sources more competitive with dynamite in terms of resolving power and signal-to-noise ratio. We use numerical modelling to explore possible improvements in Vibroseis reference-signal design, and algorithmic approaches to Mini-SOSIE stacking.

We revisit an alternative Vibroseis sweep comprising a constant frequency carrier which suffers polarity reversals according to a pseudo-random coding sequence. Numerical models allow various comparisons with the conventional swept-frequency approach. Visually, the correlation wavelet from the pseudo-random reference appears less affected by side lobes than the conventional Klauder wavelet. On the other hand the correlated pseudo-random trace is noisier away from the wavelet itself. A pseudo-random sweep built from half-cycle components has interesting theoretical possibilities, but practical implementation may be difficult.

Pseudo-random design concepts extend naturally to the Mini-SOSIE source, which stacks, in real time, numerous low-amplitude impacts, occurring at approximately random time intervals. We demonstrate the undesirable effect of non-randomness, and examine the feasibility of using predictive deconvolution to improve the randomness of the impact sequence prior to stacking.

Sign-bit stacking provides better attenuation of noise bursts than standard Mini-SOSIE stacking, although it may be prone to some amplitude distortions. A stacking procedure which incorporates a median-filtering stage appears to provide good noise-burst attenuation whilst maintaining reflection amplitudes.

Key words: pseudo-random, seismic source, Vibroseis, Mini-SOSIE

INTRODUCTION

The dynamite land-seismic source can have significant geophysical advantage in terms of signal bandwidth, particularly for targets at shallow to medium depth. However, environmental, logistical and security considerations mean that non-explosive, surface seismic sources must assume increasing future importance. This study focuses on two common surface sources. Vibroseis is the dominant surface source for petroleum seismic, while Mini-SOSIE is heavily used in coal exploration. Numerical modelling provides a useful tool for evaluating methodological variations which might improve the resolving power and signal-to-noise of such sources, making them more competitive with dynamite.

PSEUDO-RANDOM VIBROSEIS

The basic methodology of swept-frequency Vibroseis (e.g. Crawford et al., 1960; Pieuchot, 1984) has not changed significantly over several decades. This is a tribute to the success of the original concept. An alternative approach (Wischmeyer, 1966; Cunningham, 1979) employs a reference sweep built from a sinusoidal carrier signal of constant frequency. The effective bandwidth of the signal is broadened by imposing a series of polarity reversals, according to a predefined pseudo-random code, which defines the polarity of each cycle of the sweep. There are well understood code-design rules (e.g. Golomb, 1964; Strong, 2003) which result in a sweep whose autocorrelation wavelet will be optimally compressed.

An example relevant to petroleum exploration might employ 511 cycles of a 60 Hz carrier, providing a sweep length of 8.5s. Figure 1 compares the autocorrelation of such a sweep with that of a conventional swept-frequency (10-100 Hz) reference of length 8 s. A claimed advantage of the pseudo-random sweep (Cunningham, 1979) is that its autocorrelation wavelet is arguably simpler than for the conventional approach. Figure 1(a) demonstrates that this is a reasonable claim for short autocorrelation lags. An optimum pseudo-random code design results in a very compact autocorrelation pulse with only one side lobe. However, at longer autocorrelation lags, the pseudo-random reference typically yields greater correlation noise than for the conventional signal (Figure 1(b)). In general, this is an undesirable feature of the pseudo-random approach, which would impact negatively on the overall signal-to-noise of the correlated output.

The coal seismic arena provides one geological scenario where the pseudo-random approach may be more attractive. Since there is often a single dominant target horizon, the generation of correlation noise at long lags may be less of an issue, whilst the simpler central wavelet shape is advantageous for resolution. Figure 2 illustrates this possibility for a simple wedge model. The pseudo-random response (Figure 2(b)) is arguably simpler than the conventional swept-frequency response (Figure 2(a)).

Figure 2(c) illustrates an interesting further theoretical possibility suggested by the pseudo-random approach. Here the pseudo-random code has been applied to polarity reversals of a half-cycle of the carrier frequency (rather than full cycle). The resultant autocorrelation wavelet is very simple, consisting of a single central lobe. There are however, practical issues in implementing such a scheme, relating to the implied base-plate motions. Strong (2003) suggests that a viable system may be achievable if the pseudo-random sweep defines base-plate velocity rather than acceleration. That analysis is based on simple assumptions and requires further investigation.

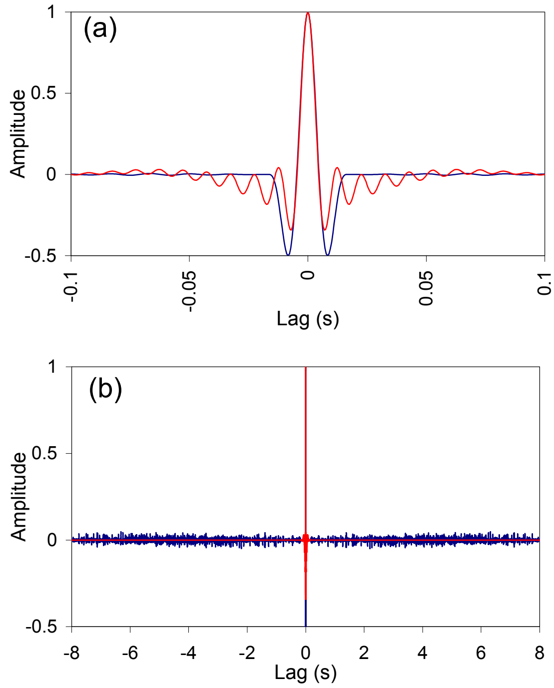

Figure 1. Autocorrelation responses for conventional sweep (10–100 Hz, 8s; in red) and pseudo-random sweep (60 Hz, 511 cycles; in blue). (a) Detail at short correlation lags, showing wavelet character. (b) Full autocorelation showing correlation noise at long lags.

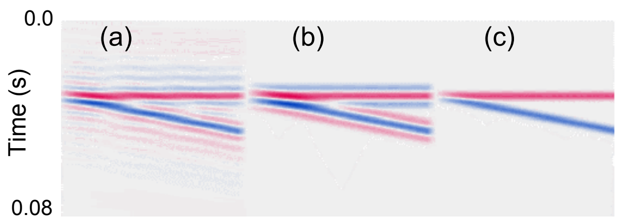

Figure 2. Zero-offset responses for simple wedge model, ranging in thickness from 0 m to 14 m (approximately one wavelength). (a) Conventional sweep (30-250 Hz, 7s); (b) Pseudo-random sweep (150 Hz, 1023 cycles); (c) Half-cycle pseudo-random sweep (150Hz, 2047 half cycles).

MINI-SOSIE

The Mini-SOSIE system (Barbier et al., 1976) uses a small road compactor to inject a large number (typically several hundred) impacts into the earth. A viable recording is then constructed by stacking the individual responses. Numerical modelling provides valuable insight into potential problems, and enhancements, for the system.

In its normal operating mode, the compactor tends to provide a relatively periodic impact sequence. However, the success of the Mini-SOSIE stacking process relies on the impacts being injected in a random fashion. Conventionally, this is achieved by the operator manipulating the throttle on the compactor, although robotic randomisers are also used.

Figure 3 models the importance of randomness in the impact sequence. In Figure 3 (a) a highly-random impact sequence yields an accurate stacked record, allowing two reflection events to be identified. When the impact series is more periodic, the output stack trace contains spurious events, additional to the true reflectors (Figure 3(b)). A non-random impact series can be accommodated to some extent if the recorded impact train is modified appropriately prior to the stacking process. As an example of this concept, the non-random impact series used to record Figure 3(b) has been subjected to predictive deconvolution, to improve randomness, prior to stacking. The resultant output (Figure 3(c)) exhibits considerable attenuation of spurious events.

Because it is a portable, non-explosive source, Mini-SOSIE is attractive for use in areas of cultural activity. In such situations high-amplitude noise can occur. Modelling can be used to investigate options for reducing the impact of such noise. Figure 4 simulates Mini-SOSIE recording in a case where there is relatively strong random noise, coupled with high-amplitude noise bursts. Figure 4(a) shows a short section of the raw unstacked data. Reflection events are obscured by random noise, and a very large noise burst occurs at 0.1s. The standard Mini-SOSIE stacking process (Figure 4(b)) recovers the two reflection events (at 0.05s and 0.15s) from the random noise, and significantly attenuates the noise burst. An alternative approach is to use sign-bit stacking (e.g. Long, 1981; O'Brien et al, 1982). A third option is to incorporate a median filter in the stack process. Both the sign-bit (Figure 4(c)) and median filter (Figure 4(d)) approaches attenuate the noise burst better than the standard stack (Figure 4(b)). On the other hand, they both tend to be slightly less effective at random-noise attenuation, compared to the standard stack.

Strong (2003) has examined the sign-bit Mini-SOSIE stacking concept in some detail. Interestingly, the system tends to maintain relative amplitudes better when there is a relatively high random noise level (as in the example of Figure 4). For unstacked Mini-SOSIE data, this will probably be the normal situation.

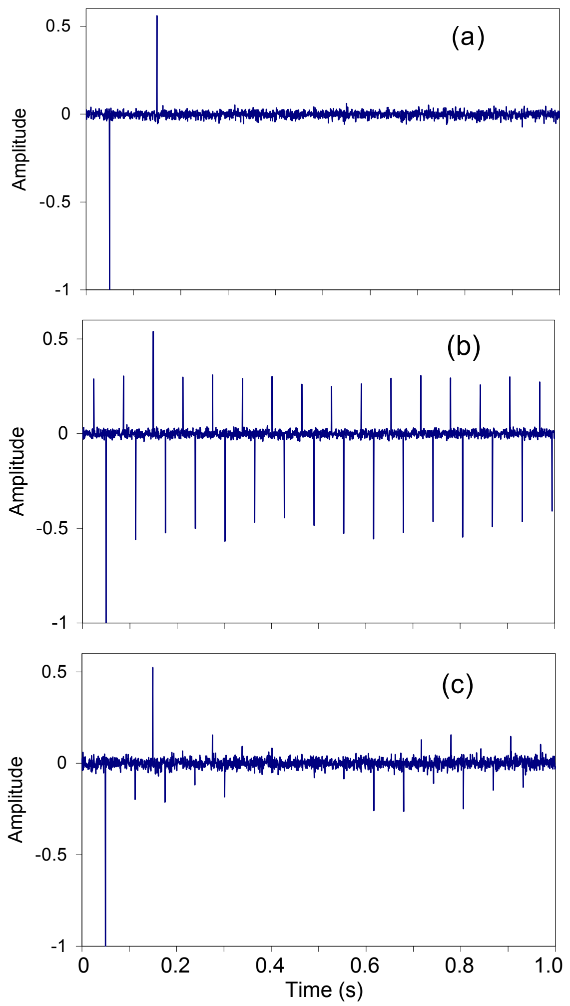

Figure 3. Stacked outputs for a model comprising two reflection spikes and random background noise. (a) Random impact sequence; (b) Periodic impact sequence; (c) Periodic impact sequence, with predictive deconvolution applied prior to stacking.

In situations where there is a lower random-noise level, sign-bit stacking can potentially yield amplitude and wavelet distortions. As an example, Figure 5(a) shows the initial segment of an unstacked data recording for a situation having a low random-noise level, coupled with a strong noise burst. The standard stack (Figure 5(b)) recovers the two reflection events (at 0.05s and 0.15s) and attenuates the noise burst significantly, but not completely. The sign-bit output in Figure 5(c) is again more successful in removing the noise burst. However, there is some amplitude distortion in the reflection wavelets. In comparison, the median-filtered stack (Figure 5(d)) attenuates the noise burst, whilst also maintaining good amplitude behaviour at the reflectors.

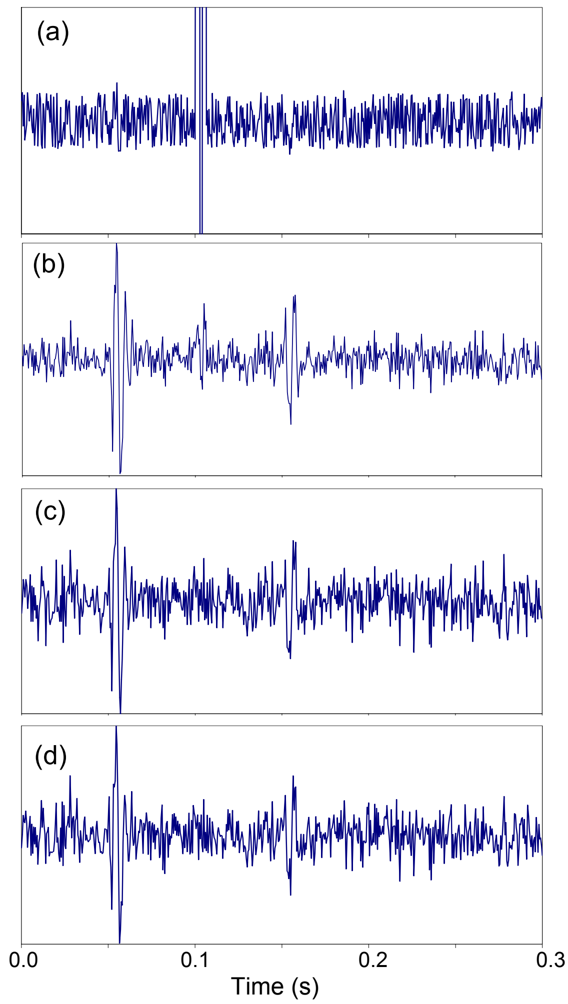

Figure 4. Simulated Mini-SOSIE stacks for high random-noise situation. (a) Initial segment of raw unstacked record showing high-amplitude noise burst (at 0.1s). Reflection events are obscured by random noise. Average amplitude of random noise is twice that of largest reflection event. Amplitude of noise burst is 100 times that of largest reflection event (noise burst is clipped for plotting purposes); (b) standard stack of full 45 s record (450 impacts); (c) sign-bit stack ; (d) median-filter stack.

CONCLUSIONS

Numerical modelling provides useful insight into the operation of pseudo-random land seismic sources. A number of avenues for potential improvement have been identified.

The pseudo-random Vibroseis sweep does produce a simplified autocorrelation wavelet when compared to the conventional swept frequency approach. It is, however, prone to greater correlation noise at long correlation lags. This characteristic may be less of a problem in situations where there are a small number of strong reflectors, such as in coal imagery. A novel approach based on pseudo-random coding of a half-cycle carrier is theoretically attractive in terms of wavelet character, although practical implementation of such a sweep may be difficult.

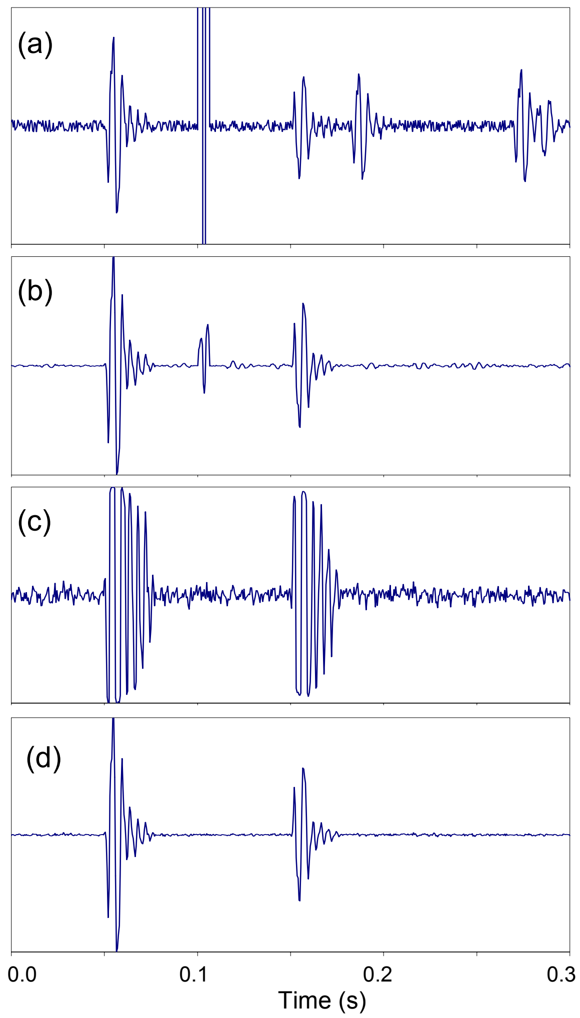

Figure 5 Simulated Mini-SOSIE stacks for low random-noise situation. (a) Initial segment of a raw unstacked record, showing a large amplitude noise burst (at 0.1s) and several reflection events. The average amplitude of random noise is 5% of the amplitude of the largest reflection event. The amplitude of the noise burst is 100 times that of the largest reflection event (noise burst is clipped for plotting purposes); (b) standard stack of full 45 second recording (450 impacts); (c) sign-bit stack ; (d) median-filter stack.

The Mini-SOSIE stack process is seriously degraded if the impact sequence is non-random. Non randomness can be accommodated to some extent if the recorded impact sequence is pre-conditioned prior to stacking. One potentially useful scheme applies predictive deconvolution to the impact sequence prior to stacking.

The standard Mini-SOSIE stacking scheme successfully recovers reflection events in high background noise, although very large noise bursts can survive the stacking process. Sign-bit stacking provides better attenuation of noise bursts. Interestingly, the sign-bit process may be prone to some amplitude distortions where signal-to-noise conditions are favourable. A stacking procedure which incorporates a median-filtering stage appears to provide good noise-burst attenuation whilst maintaining relative amplitudes in all noise situations.

Note that procedures such as deconvolution and median filtering would not be directly applicable to the real-time stacking commonly used for Mini-SOSIE, and would require interim storage of unstacked data.

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