Improved operational efficiency using spread spectrum sweeps for marine vibrators

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Summary

An encoded sweep strategy is described that enables efficient and flexible opportunities for towed marine vibrator seismic surveys capable of generating arbitrary signals with full phase control over the frequency of interest to seismic imaging. Continuous source operation with orthogonal signal sequences enable the use of many simultaneous marine vibrator units whilst towing at efficient vessel speed. Post-survey, the desired shot point interval for the optimized imaging of a particular depth range can be optimized by combining varying numbers of sub-sequences: shallow targets are imaged with short sub-sweeps and therefore short shot point interval, and deeper targets are imaged with longer sub-sweeps, longer shot point interval, and higher signal amplitude by virtue of longer sweeps. Overall, this strategy may enable less marine vibrator units by comparison to that required to achieve a given sound pressure level (SPL) using conventional sweep strategies, have significantly lower environmental impact than any air gun source design, and enable greatly improved operational efficiency.

Introduction

Tenghamn (2006) describes a flextensional marine vibrator (MV) concept that can be towed as an alternative to air guns in marine seismic surveys. An electric driver mechanism translates a sweep signal into a controlled displacement of the water around the hollow shell of the MV unit, modified in real time using an iterative learning circuit (ILC) feedback mechanism that simultaneously maintains a designated emitted signal spectrum whilst attenuating unwanted harmonics above the seismic frequency range of interest by more than 40 dB. By careful engineering, two resonance frequencies are created within the seismic frequency range of interest, thereby enabling a highly efficient source wavefield generation with relatively uniform amplitudes over a frequency range of about 5-100 Hz using two complementary MV units: a larger ‘Subtone’ unit emitting 5-25 Hz and a smaller ‘Triton’ unit emitting 25-100 Hz. Each MV unit has a far-field amplitude [A(f)] that can be approximated as follows:

$$A(f) = SPL - 10\log_{10}(\text{sweep bandwidth}) + 10\log_{10}(\text{sweep length}) \qquad (1)$$

For a given SPL, a longer sweep length increases the energy emitted, and a broader bandwidth dilutes the energy over more frequencies.

Whilst ‘conventional’ MV acquisition uses sequential sweeps, each sweep using a common master signal, probably separated by listening times, we propose instead to use continuous sweeps wherein orthogonal sweeps sequences are used. An example strategy would use Gold sequences (Dixon, 1994); a type a type of binary sequence used in telecommunication (CDMA) and satellite navigation (GPS). Gold sequences have bounded small cross-correlation within a set, which is useful when multiple devices are broadcasting in the same frequency range (see Figure 1).

The ILC aspect of the MV concept described by Tenghamn (2006) enables the generation of arbitrary signals with full phase control over the entire frequency band of interest for seismic imaging, making it possible to use advanced spread spectrum signal encoding for MV operations. Figure 2 shows a comparison of a linear sweep vs. a spread spectrum sweep using a compact MV array: note that both sweeps contain the same signal bandwidth. A strategy is introduced below that may significantly SPL per Hz whilst simultaneously improving operational efficiency.

Spread Spectrum Sweep Strategy

As schematically shown in Figure 3, spread spectrum sweep signals are designed and denoted here as a ‘full sequence’; for example, 40 seconds in duration. The full sequence comprises sub-sequences, for example, Gold sequences, that can be separated by correlation in signal processing, and accordingly combined as required. The length of each sub-sequence is indicative of the shortest achievable shot point (SP) interval after autocorrelation. Increasing numbers of (sequential) sub-sequences can be combined to achieve higher amplitudes for deeper targets—sacrificing spatial resolution (via coarser effective SP interval) without unacceptably compromising seismic image quality because of the lower frequencies available at depth after attenuation.

It can be easily demonstrated how longer sub-sequences will correspond to higher amplitudes at the depth being imaged. Let a reference scenario be the use of 5 second linear sweeps followed by 5 second listening time. If a continuous sweep strategy is used with a new orthogonal sub-sequence every 5 seconds, an additional 3 dB amplitude will be available for imaging. Furthermore, increasing the sub-sequence length to 10 seconds, or 20 seconds, or 40 seconds (i.e. doubling) will correspondingly increase the amplitude in each scenario by 3 dB as defined in equation (1), such that a 40 second sub-sequence enables the amplitudes to be 12 dB higher than the reference scenario. It follows that the number of MV units being used could be reduced by a factor of four without reducing the effective source amplitude by comparison to the reference scenario: the MV array used could therefore be compact and logistically very efficient. From the perspective of operational flexibility small and lower cost source vessels could then be considered for multi-vessel operations such as wide-azimuth (WAZ) and full-azimuth (FAZ) towed streamer surveys, or ocean bottom node (OBN) surveys.

Figure 3 simulates the use of different sub-sequence lengths for the optimized imaging of different depths. Note that the

10.1190/segam2018-2996421.1

use of long sub-sequences (Figures 3B and 3C) is appropriate for large depths but the spatial frequency of shallow events is compromised. In contrast, the use of short sub-sequences (Figures 3D and 3E) is appropriate for the higher resolution imaging of shallow events. In both scenarios the different outcomes are achieved using the same continuous spread spectrum sweep 'full sequence' without having to synchronise the sweep design to any designated spatial shot points.

MV Field Tests with Spread Spectrum Sweeps

Spread spectrum sweeps were tested in the field several years ago using a previous generation of MVs. One stationary ocean bottom cable was traversed with an airgun array (600 in^3 volume) and MVs (separately) emitting both linear and spread spectrum sweeps. Selected acquisition parameters are summarized in the table.

Number of receivers	128
Receiver distance	12.5 m
Water depth	15 m
Recording length	11 s linear sweep 12 s spr-spectrum sweeps
Number of sweeps	290 linear sweeps 307 spr-spectrum sweeps
Water depth	14 - 15 m
Sweep length	6 s linear sweeps 6.12 s spr-spectrum sweeps
Sweep frequencies	8-90 Hz

The spread spectrum sweep line is compared to the airgun line in Figure 4, showing the potential for spread spectrum signals to create high quality data. Note that this MV version lacked the ILC phase control of the current version, hence the somewhat penalized deeper amplitudes in the lower part of Figure 4 (right panel). An advanced ILC system (Mougenot et al., 2017) now controls the phase to within ±1° over all frequencies of interest.

Environmental Considerations

Modern air gun arrays use a combination of different air gun volumes during 'array tuning' (Dragoset, 2000) to yield a reasonably uniform amplitude over the seismic frequency range of interest with a peak SPL in the range of 240-250 dB (re 1 μPa at 1 m). In contrast, the MV concept of Tenghamn (2006) can yield a comparably flat spectrum using only one 'Subtone' and one 'Triton' unit. To meet the requirement of an amplitude spectrum close to 200 dB re 1 μPa, as specified by the Marine Vibrator Joint Industry Project (MVJIP) standards described in Schostak and Jenkerson (2015), a total of 12 MV units are needed: 4 Subtone and 12 Triton. As the peak SPL of 200 dB (re 1 μPa) corresponds to a resonance frequency in the output spectrum of each Triton MV, it follows that the peak SPL of 8 Triton units operating with conventional 25-100 Hz sweeps will be 218 dB (re 1 μPa), which is about 20-30 dB less than a typical air gun array.

However, using equation (1), it follows that as a spread spectrum signals spreads the frequencies out in time in addition to spreading the energy in time, the peak amplitude using spread spectrum sweeps will be $-10\log_{10}(75) = -19$ dB (re 1 μPa) lower than the scenario using conventional sweeps. Overall, the use of a MV array configured to the specifications of the MVJIP and using the spread spectrum sweep strategy described here would yield peak SPL in the range of 40-50 dB (re 1 μPa) lower than a conventional air gun array (i.e. 90-99% lower). As also discussed in an earlier section, this benefit could also be achieved in a highly efficient manner.

Conclusions

Continuous sweep operations with orthogonal spread spectrum sweeps may enable less marine vibrator units to be used without reducing the effective amplitude of the emitted source wavefield by comparison to conventional sweep strategies. Furthermore, the sweeps are not synchronized to any spatial shot point locations, allowing more efficient acquisition. Orthogonal sub-sequences of varying length can be selected in signal processing to optimize the imaging of different depths: shallow targets are imaged with short sub-sweeps and therefore short shot point interval, and deeper targets are imaged with longer sub-sweeps, longer shot point interval, and higher signal amplitude by virtue of longer sweeps. Overall, this strategy may enable less marine vibrator units by comparison to that required to achieve a given peak output using conventional sweeps, enabling new opportunities for how source arrays are deployed.

Acknowledgements

Thanks to PGS for permission to publish this material.

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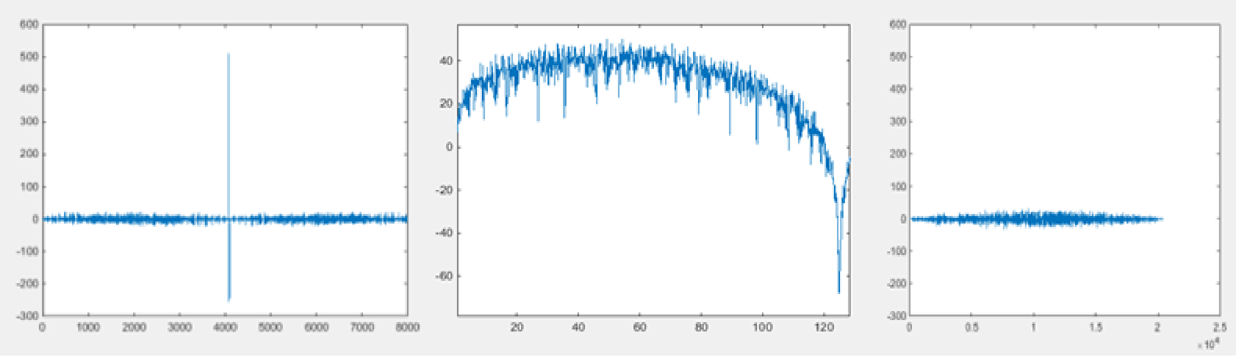

Figure 1 *(left) Autocorrelation of Gold sequence G511a; (middle) Amplitude spectrum for Gold sequence G511a; and (right) Cross-correlation of Gold sequences G511a and G511b.*

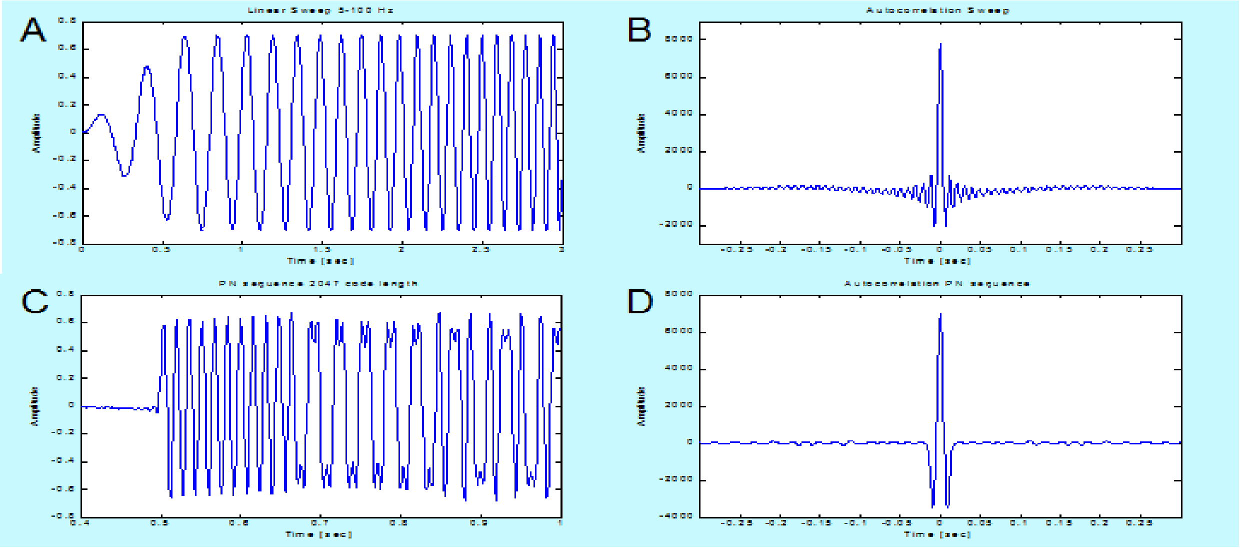

Figure 2 *(A) Linear MV sweep signal; (B) Autocorrelation of A; (C) Spread spectrum MV sweep; and (D) Autocorrelation of C.*

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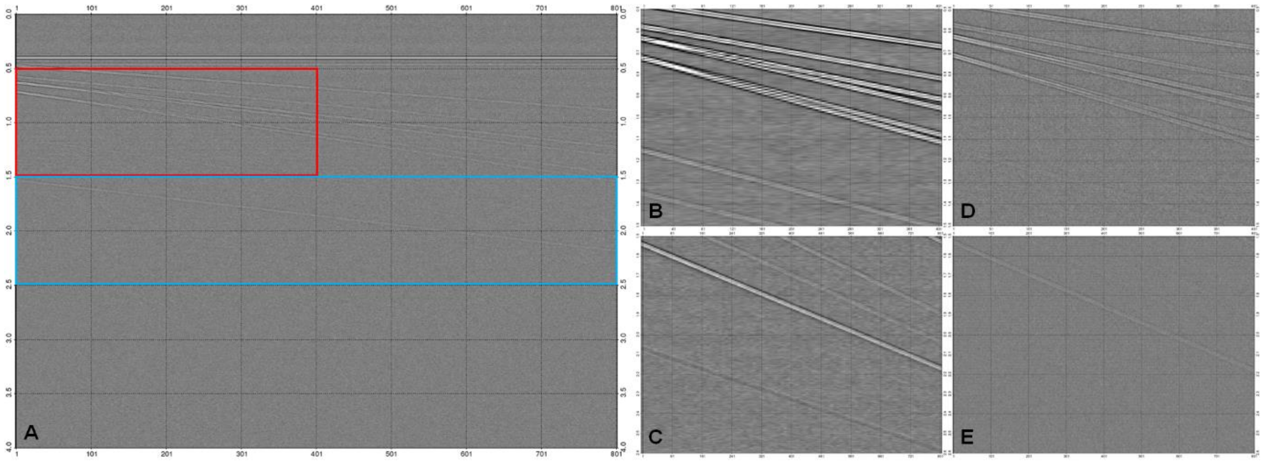

Figure 3 *Synthetic data spread spectrum simulations: (A) 0-4 s synthetic stack generated with the autocorrelation of a 5 s sub-sequence (note the shallow and deep windows used for B-D); (B) 0.5-1.5 s result from a 40 s sub-sequence and 100 m SP interval; (C) 1.5-2.5 s version of B;*

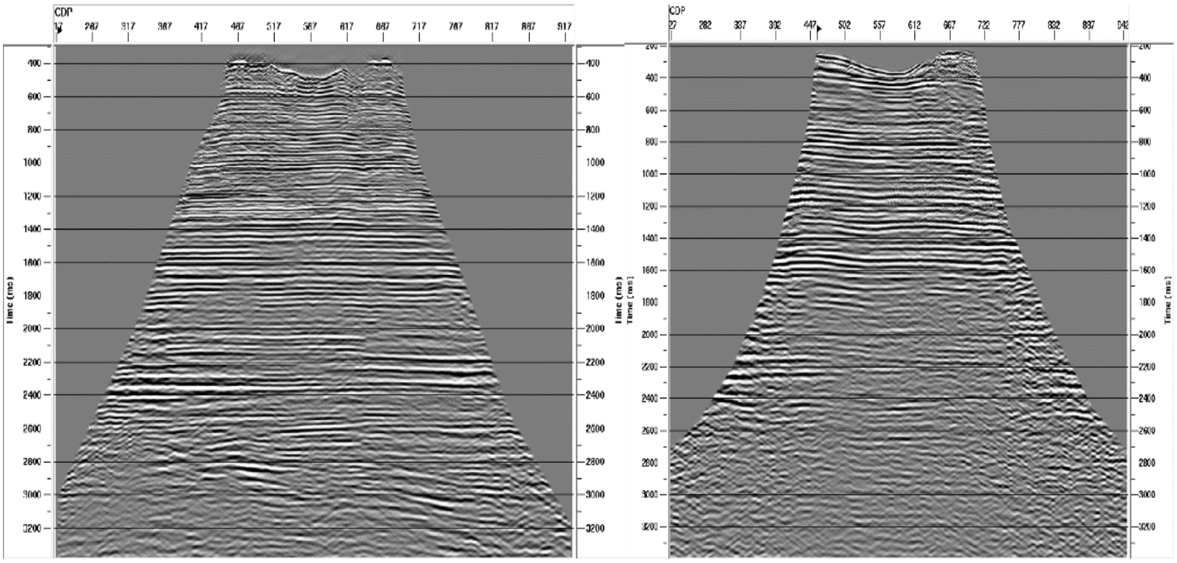

Figure 4 *Stacked sections of the vertical OBC component using an air gun array (left) and spread spectrum marine vibrator sweeps (right). The lines were acquired with different crossline offset to the receiver line, hence the time shift between the sections.*

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