Full-wave vibroseis acquisition with various controllable sweep signals emitted by lightweight electric vibrator

I. Korotkov[1], R. Wang[1], A. Zhukov[1]

[1] Independent researcher

Summary

We conducted extensive experiments to investigate how differently controlled sweep signals can improve full-wave seismic images with the same acquisition parameters compared to standard linear sweep. As a practical seismic source device, we used a lightweight electric vibrator operating in P- and S-wave generation modes to record a 220-m-long line along a university campus sidewalk. Seven different sweeps were tested, including one random signal and five differently coded pseudorandom signals, as these signals are suitable for increasing productivity when acquiring large-scale 3D surveys. We also tested the deterministic Ricker wavelet equivalent sweep for its potential to improve the correlation of the reflected signals. Experimental results show that controlled sweeps can significantly improve seismic images, and that pseudorandom signals have the potential to improve both productivity and image quality.

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Introduction

Hydraulic vibration sources are widely used in large-scale P-wave 3D surveys and are the industry standard for seismic surveys in oil and gas exploration. The heavy vibration unit, weighing 30-60 tons, is controlled by a built-in electronic controller with feedback and transmits a predetermined frequency-modulated signal (sweep) with a duration of 15 to 20 seconds as precisely as possible. Standard linear sweeps do not take into account the effects of signal propagation in the geological environment, such as frequency-dependent absorption and phase dispersion. To overcome this drawback, a fully controlled sweep method was developed (Korotkov et al., 2022). This approach based on a sweep, which is an inverse filter of the geological environment. The important challenge of increasing the productivity of vibroseismic surveys is solved by the independent simultaneous sweep or ISS method (Howe et al., 2008). This technique often uses mutually uncorrelated random or pseudorandom sweep signals, which reduce the effects of simultaneously acting sources through mutual reduction.
The electromagnetic vibrator has significantly less weight; the mass of the vibrator unit is only 90 kg. It is much simpler in design; its vibrating unit is driven by a linear electric motor (Noorlandt et al. 2015), which transmits electromagnetic force to a reaction mass connected to the plate via a damping spring. To excite horizontal vibrations (S waves), we need to manually rotate the vibrating unit 90 degrees before shear wave line shooting. Such sources are mainly used for shallow engineering seismic surveys where multicomponent data play an important role in determining the lithology from the top of the section to a depth of several hundred meters. When conducting field tests using electric vibrators, it does not require as much effort to organize a standard field crew as it does with heavy hydraulic sources. Therefore, we decided to perform extensive experiments using a lightweight vibe to test the controllability with different sweep signals in full-wave mode. It took only two days to collect full-wave data from eight different signals. The results of these experiments will be useful for both shallow full-wave and large-scale P-wave high-production seismic surveys.

Signals description

A standard linear sweep from 3 to 100 Hz served as the basis for comparison with the other seven signals tested (Figure 1, a). Random shuffle sweep (Figure 1, b) can be implemented with virtually any vibration source and have already been successfully tested to improve the productivity of vibroseismic surveys (Zhukov et al., 2017). However, to improve the inherent correlation properties of shuffle sweep, its length needs to be increased to 40–60 seconds, which limits ISS productivity gain (Korotkov et al., 2023). It is known from research in radio engineering (Varakin, 1985) that pseudorandom sequences whose length is shorter than random have similar or improved inherent correlation properties and are more tolerant to ambient noise. This means that it is possible to construct relatively short sweeps based on known m-sequences that are as good as or better than random shuffle sweeps, while further improving ISS performance. That is why we designed five sweeps like this. Two of them were generated from the 3-100 Hz linear sweep by changing the polarity of full cycle (Fullcycle, Figure 1, c) or half cycle (Halfcycle, Figure 1, d) fragments, which correspond to minus code of the m-sequence. In this way, we attempted to preserve the frequency content of the linear sweep. For the other three, single frequency sinusoidal sweeps of 30 50 and 70 Hz were used. We manipulated polarity of their half cycle fragments according to the code sign at the corresponding m-sequence code time (Sin30Hz, Sin50Hz and Sin70Hz, Figure 1, e, f and g). The last, seventh, sweep was the equivalent of the theoretical Ricker wavelet with a central frequency of 50 Hz (Figure 1, h). We consider such signal as optimal matched filter capable for better detecting reflected signals of a given shape in the recorded wave field.

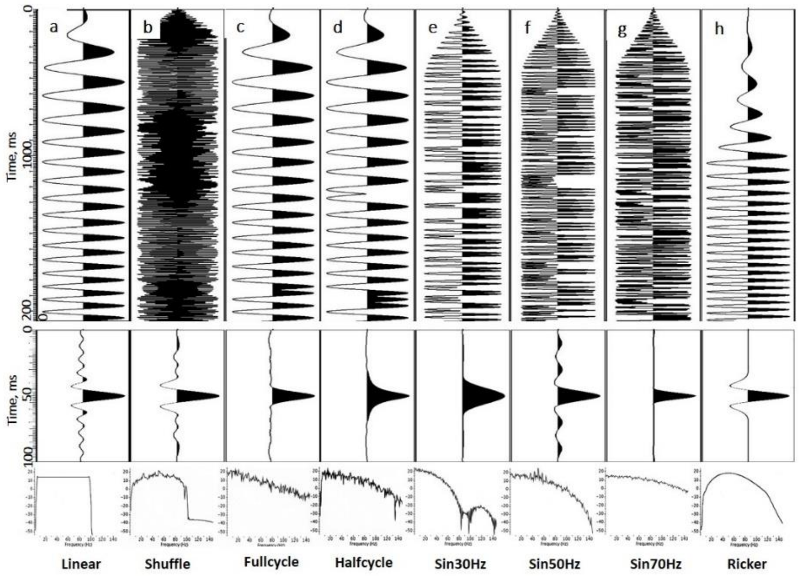

***Figure 1** Test sweep signals (at the top), their autocorrelation functions (in the middle) and spectra (at the bottom).*

Data acquisition

Figure 2 shows line location photo (above) and the main elements of the experiment equipment (below). We shot an experimental two-dimensional 222.5 meters seismic line in urban environment along asphalt sidewalk of the university campus (Figure 2, a). The Lightning electromechanical vibrator emitted both shear and compression waves (Figure 2, d and e). The all-terrain buggy vehicle Forester served as the carrier for the electromechanical vibrator unit (Figure 2, b). We installed the Scout three-component wireless nodes (Figure 2, c) at every 2.5 meters along the line and 1 m from the side in the lawn for stationary receiver spread wireless reflected and converted data recording. We passed the line two times, first pass was P-wave mode (vertical baseplate position) and another was S-wave mode, after vibration unit 90 degrees rotation. Each pass included subsequent sourcing of the eight sweeps described above at every 5 meters shot point distance. All sweeps were 20 s length except of random shuffle 40 s sweep, which usually required longer length in previous tests and we intended to compare it with shorter pseudorandom ones in term of acquisition productivity. We also established all acquisition listening time as 5 seconds.

***Figure 2** Line location and test equipment.*

Data processing and results

First, we selected from full 6C recorded wave field only those components, which represent pure P-P, and S-S mono wave type reflected data with the same polarisation. It was Z-Z vertical recorded component for P waves and Y-Y horizontal component for S waves. After data selection and correlation we passed all correlograms through the same rather simple processing flow which included gain recovery, spiking decon, statics, denoise, NMO, CMP stack and post stack enhancements. Figure 3 demonstrates time sections from the eight signals after data processing, both P-P (above) and S-S waves (below). It is visible, that in spite of the same processing sequence including deconvolution the results are quite different. All seven test signal results (Figure 3, b-h) compete with Linear sweep time sections (Figure 3, a) and show better but rather variable reflectivity details and deeper penetration. Pseudorandom sweeps coded from monochromatic sine 30 50 and 70 Hz frequencies (Figure 3, e, f and g) show section resolution change that means we can control acquisition results by changing only this frequency parameter. Figure 3 (h) shows Ricker sweep time sections which are more contrast and detailed comparative to Linear sweep results (Figure 3, a) because of Ricker signal probably better worked as optimal matched filter, as expected.

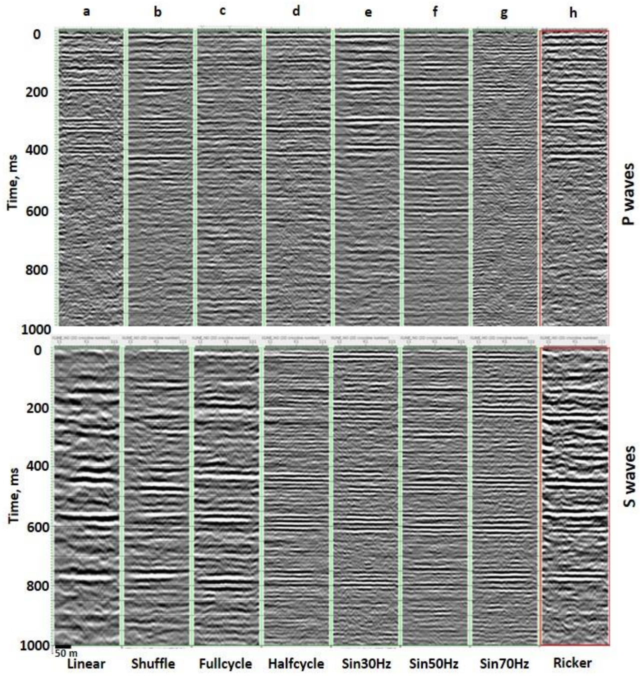

Figure 3 *P (above) and S (below) wave time sections obtained from different sweep signals.*

P and S wave reflectors from the same geological boundaries were identified on corresponding time sections and S-S images were converted to P-P time according to standard event registration technique, which is conventionally applied during full wave data processing workflow. Average Vp/Vs ratio estimated after the registration process was about 2.0. At the final step, we converted registered time section to depth with P wave RMS velocities. Figure 4 demonstrates comparison of P and S waves depth sections obtained from Linear (a and b) and pseudorandom Sin50Hz (c and d) sweep signals. Linear sweep sections looks noisy and it is difficult but possible to identify geological boundaries there. In contrast to the Linear sweep sections, the pseudorandom sweep results perfectly match to the geology section shown on Figure 4 e. We can clearly see the Devonian top at the 400 m depth on the new pseudorandom sweep result (Figure 4, d, black arrow). This boundary has previously been poorly imaged on near- surface seismic sections in this region.

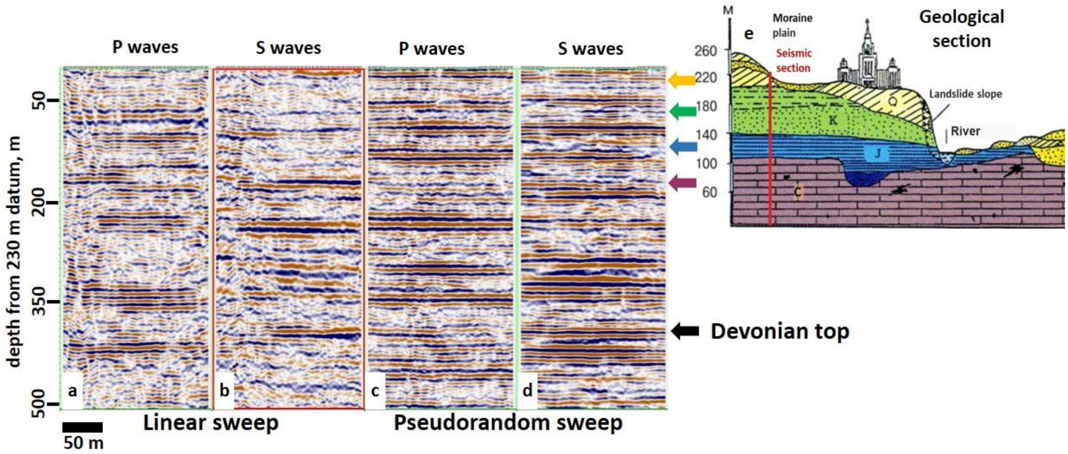

Figure 4 *Comparison of Linear (a and b) and Sin50Hz (c and d) P (a and c) and S (b and d) wave depth sections. Geological cross-section (e) with seismic sections position (red line) and geological intervals (colour arrows) that matched to the pseudorandom sweep seismic sections (c and d).*

Conclusions

In general, it can be concluded that the possibility of controlled sweep emitting itself allows a significant improvement in the obtained seismic images without changing the acquisition effort. Differently coded short pseudorandom sweeps demonstrate performance compared to long random sweeps that will improve both the productivity of ISS and image quality. Pseudorandom sweeps can be flexibly controlled and appear to be more resistant to propagating noise. A deterministic Ricker sweep focuses the signal propagation within a specific amplitude spectrum, allowing for better detection of reflected signals through standard correlation. The lightweight electrical vibe has demonstrated its capabilities for near-surface full-wave studies in urban environments and can serve as a rapid test instrument for such extended controlled signal source experiments.

References

Howe, D., Allen, A. J., Foster, M. S., Jack, I. J., and Taylor, B. [2008] Independent Simultaneous Sweeping. *70th EAGE Conference and Exhibition incorporating SPE EUROPEC*, cp-40-00048.

Korotkov, I., Zhukov, A., and Nekrasov, I. [2022] Vibroseis acquisition with fully controllable sweep signals based on borehole VSP data analysis. *83th EAGE Annual Conference & Exhibition, Extended Abstracts*, 276.

Korotkov, I., Zhukov, A., Gafarov, R. and Siraev, I. [2023] Increasing resolution and productivity of Vibroseis methods with enhanced simultaneous sweeps and cabled acquisition. *84th EAGE Annual Conference & Exhibition. Extended Abstracts*, 195.

Noorlandt, R., Drijkoningen, G., Dams, J. and Jenneskens, R. [2015] A seismic vertical vibrator driven by linear synchronous motors. *Geophysics*, **80**, no. 2, EN57–EN67.

Varakin, L. [1985] Communication systems with noise-like signals. *Radio and communication*, 384.

Zhukov, A., Korotkov, I., Sidenko, E., Nekrasov, I., Gridin, P. and Galikeev, T. [2017] Simultaneous pseudo-random shuffle-sweep generation and increased seismic data acquisition productivity. *SEG Technical Program, Expanded Abstracts*, 151-155.