Vibroseis acquisition with fully controllable sweep signals based on borehole VSP data analysis

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Introduction

Seismic exploration is an active method, which creates a seismic wave field in the geological environment using various methods of generating artificial displacement by one or another seismic source type or a group of sources. Seismic sources such as an explosion in a well, a pneumatic source or a weight drop are capable of generating short impulse effects (signals) of significant amplitude several tens of milliseconds long. The ability to control such signals is strongly limited only by the intensity of the impact due to the amount of charge, the volume of airgun chamber or the hummer weight. A vibration source is a recognized instrument of generating seismic signals several tens of seconds long, in which the vibration amplitude is constant in time, and a given frequency range is emitted into the environment using frequency modulation according to a given time-frequency function.

Potentially, the vibration source is the only fully controllable seismic source whose control capabilities depend solely on the electronic controller of the vibrator's hydraulic system. The vibrocontroller drives the hydraulic and mechanical components of the vibration source by real-time feedback from the measurements of the acceleration sensors installed on the main elements of the vibration unit - the plate and the reactive mass. The main task of the control is the maximum correspondence of the feedback signals weighted sum (i.e. ground force) to the given time-frequency law and its phase matching to the electrical reference sweep signal while honoring hydraulic system limits.

For decades, vibroseis surveys were acquired using sweep signals with simple linear or nonlinear, mainly logarithmic, time-frequency dependences, which did not fully realize the potential of the vibroseis prospecting in general. Adaptively controlled vibroseis acquisition, which uses sweep derived from reflected wave's amplitude spectrum analysis, was first demonstrated in (Zhukov, 2013). Further development of vibrator source control methods were aimed at geophysical control of both the amplitude and phase spectra of the emitted sweep signals. Korotkov and Zhukov (2020) demonstrated possibility and results of sweep signal emission, which is equivalent to an inverse Q filter and takes into account frequency dependent absorption and phase dispersion. The sweep signal that is equivalent to the minimum phase impulse was presented in (Korotkov et al., 2021).

This paper demonstrates the possibility of constructing various inverse filter sweeps based on the VSP data, obtained from standard linear sweep signal in a wide frequency range. Standard VSP observations make it possible to estimate the signal, which propagated from a source located on the surface down to the reservoir level. It is possible to design various inverse filters, which compensate for frequency-dependent amplitude losses and phase distortions that occur during the propagation of the original signal through the subsurface. The full impulse response of the inverse filter is converted to the equivalent sweep signal, which is then emitted into the subsurface by the advanced vibrator controller. The VSP results obtained using fully controlled sweeps demonstrate improved reflection resolution and phase correction, which are achieved directly in the field. Such sweep signals can later be used for 3D surface seismic survey acquisition. Since the signals were derived from the data recorded at the internal points of the subsurface, the results of the surface seismic survey will match the well observations of the VSP as much as possible, while simultaneously converging the resolution of these two seismic methods helping spreading the near-well information extracted from the VSP in the space between the wells.

Inverse filter sweeps

An initial VSP dataset is required to assess changes in seismic signals during their propagation from the surface to the interior points of the geological environment. It is possible to use VSP data already existing at the time of new fieldwork for extracting signals at different levels and estimating such parameters as amplitude and phase Q factors. However, vintage data does not always have a sufficiently wide frequency range to work with such modern broadband seismic technologies like described in (Galikeev et al., 2019). Therefore, in the general case, the proposed method provides for preliminary registration of broadband data from a vibration source with a standard linear sweep during experimental work. Based on the preliminary data, the signal of the downgoing wave is extracted for calculating the deterministic inverse filter and the statistical deconvolution window is determined. Before calculating the signal and inverse filters, the VSP seismogram was flattened by the first arrivals of the direct downgoing wave with a time reduction of 1000 ms. (Figure 1a). The signal (Figure 1b, left) for calculating the deterministic filter (Figure 1b, middle) was estimated by stacking the direct wave in a narrow window of 980 - 1050 ms, while a wider window is 900 - 1500 ms. was chosen to calculate the statistical deconvolution operator (Figure 1b, right) from the VSP seismogram shown in Figure 1a.

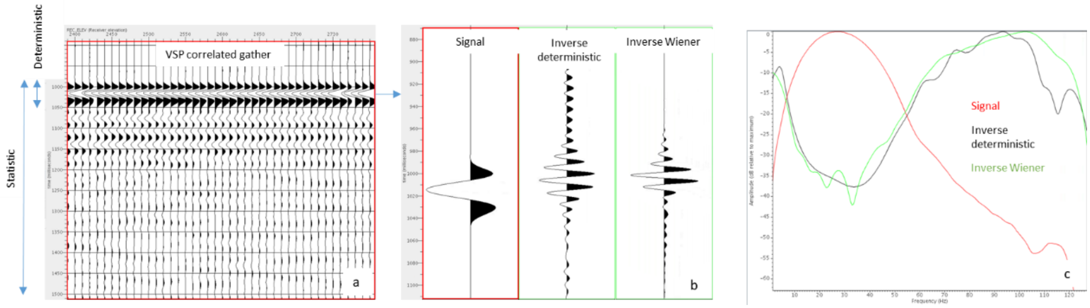

Figure 1 Signal extraction and calculation of inverse filters: (a) VSP correlogram, flattened by first breaks, (b) extracted signal (left), impulse responses of deterministic (middle) and Wiener statistical (right) inverse filters and (c) amplitude spectra of the signal (red) and the filters (black and green).

The shapes of inverse filter amplitude spectra (Figure 1c, black and green) are inverse to the extracted signal spectrum (Figure 1c, red), as expectable.

The algorithm for conversion of any pulse into an equivalent sweep consists of three main stages. At the first stage, a basic low dwell linear sweep (Figure 2c, top) is formed from Ricker wavelet (Figure 2a, top), which has a flat amplitude spectrum in a given frequency range. At the second stage, the time-frequency law is calculated, which fully corresponds to the amplitude spectrum of the inverse filter signal shown in Figure 2b (middle). The final step modifies the base sweep by stretching-squeezing of quasi-instantaneous sweep time intervals according to the difference between the linear and new time-frequency laws. The algorithm simultaneously adds time delays, which corresponds to the phase spectrum of the inverse filter signal, to the each modified time interval. Additionally, the algorithm provides for the condition that the envelope of the base sweep remains unchanged after its modification. Thus, the formation of a sweep having a given amplitude and phase - frequency characteristics is performed using only frequency modulation in order to maintain a predetermined force during vibration. The result of the conversion is shown on Figure 2 (c, middle).

The linear sweep formula (Aldridge, 1992) is applied for calculation of each sweep's segment:

$$\boldsymbol{s}(\boldsymbol{t}) = \boldsymbol{a}(\boldsymbol{t})\boldsymbol{cos}(\boldsymbol{\varphi_0} + \boldsymbol{\varphi}(\boldsymbol{t})), \tag{1}$$

where $a(t)$ is the envelope of the base sweep which honors a low dwell interval also, φ_0 and $\varphi(t)$ are the initial phase and current phase function.

The current phase of the sweep segment is defined as a function:

$$\varphi(t) = 2\pi\left(f_0 t + \frac{bt^2}{2}\right) + \Delta\varphi(t), \tag{2}$$

where t is current time, $f_0 = \frac{f_1 + f_2}{2}$, f_1 is start frequency, f_2 is end frequency, $b = \frac{f_2 - f_1}{\mathrm{T}}$, where T is segment duration and $\Delta\varphi(t)$ is added phase function of the impulse response.

To preserve the effect of phase compensation by the inverse filter after it is emitted into the geological environment, the sweep which is intended for the correlation of recorded vibrograms with (Figure 2c, bottom) is calculated using the zero-phase equivalent of the inverse filter (Figure 2a, bottom). In this case, $\Delta\boldsymbol{\varphi}(\boldsymbol{t}) = \mathbf{0}$ (2). Thus, the method provides for the simultaneous calculation of two sweeps for two vibrator controller components known as the decoder and the encoder.

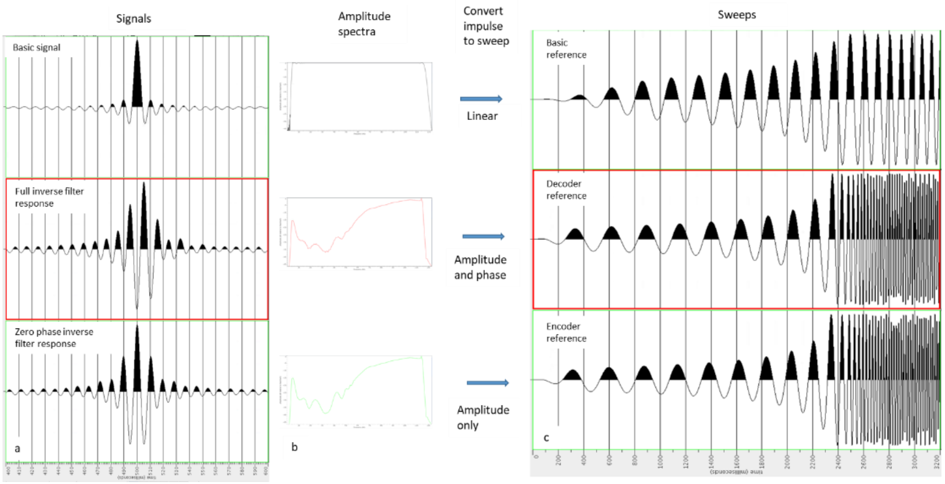

Figure 2 Impulse to sweep conversion. Signal signatures (a): base (top), full amplitude - phase (middle) and amplitude only (bottom) inverse filters. Amplitude spectra for calculating time-frequency relationships (b). Sweeps (the first 3.2 of 16 sec) (c): basic carrier (top), vibrator reference sweep (decoder, middle) and for correlation with registered vibrograms (encoder,bottom).

Field results

VSP acquisition was carried out in the depth interval 0-3000 m in a new well within a large gas field on the Yamal Peninsula. The tasks of the fieldwork included comparison of the results obtained from pulse and vibrator sources as well as checking the full controllability of the vibrator source using the new GDS-II controller, which allows sweep emitting with any amplitude-phase characteristic in a given wide frequency band including inverse filter sweeps. The range of the vibrator frequencies was 3-120 Hz. The VSP sources included Malysh air gun with a working pressure of 14 MPa and a chamber volume of 1.8 dm^3 and a group of two Nomad 65 Neo vibrators equipped with two portable GDS-II controllers. Figure 3 shows VSP field gathers from different sources and signals. We can see, from the left to the right (Figure 3), a gradual increase in the resolution of the downgoing and upgoing wave packets during the transition from air gun source (Figure 3, a) through the low dwell linear sweep (Figure 3, b) to the two inverse filter sweeps (Figure 3, c and d). The amplitude spectra shown in Figure 4 demonstrate expectable spectral expansion and flattening in case of sweep signals (red, green and blue) in comparison with the spectrum from the air gun source (black).

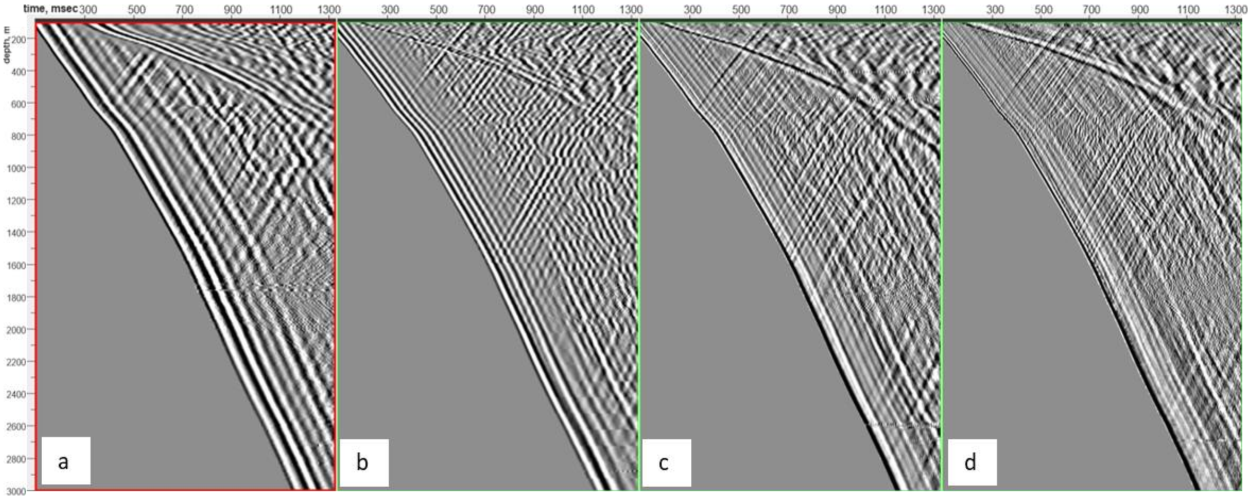

Figure 3 VSP field seismograms: (a) impulse source, (b) low dwell linear sweep 3-120 Hz, (c) sweep as a deterministic inverse filter, (d) sweep as a statistical inverse filter.

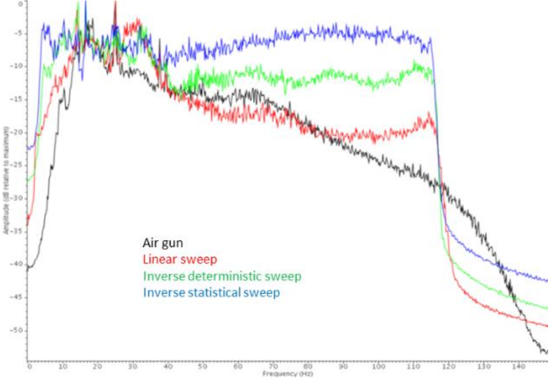

Figure 4 Amplitude spectra of VSP field seismograms: impulse source (black), low dwell linear sweep 3-120 Hz (red), sweep as a deterministic inverse filter (green), sweep as a statistical inverse filter (blue).

Conclusions

Analysis of the seismic signal within the subsurface from VSP data provides a reliable estimate of the signal loss while it propagates from the surface. The vibroseis technology, which allows emitting a seismic signal of any given signature by seismic vibrator, is created. The technology includes construction of the full inverse filter equivalent sweep and then emitting it into the subsurface to compensate for the signal loss during it propagation trough the subsurface. The proper vibrator controller is required for providing of frequency modulated low dwell and nonlinear amplitude and phase regimes. The new, fully controlled signals allow significant improvement the quality of both VSP and surface seismic data. Well-related seismic signals could further provide a natural integration of surface and borehole seismic and log methods.

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