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ASAP

Overview of efficient Vibroseis acquisition methods

Claudio BAGAINI*

Many methods have been developed in the past 25 years to speed up Vibroseis acquisition. I give an overview of the most promising ones and propose a classification of them in three categories: simultaneous shooting, cascaded sweeps and slip sweeps. The main features of these methods are summarized and some criteria for the selection of the most suitable are introduced.

Keywords: separation, productivity, sweep, attenuation

1. Introduction

The progress made in the last two decades in Vibroseis productivity has been mainly due to the recording system channel count, which, for a typical heavy-effort 3-D seismic crew, increased almost two orders of magnitude. On the source side, even though more powerful seismic vibrators have allowed reduction of the sweep lengths, this reduction can be quantified in percentages rather than orders of magnitude. A substantial increase of Vibroseis productivity from the source side can only be obtained with more than one vibrator or group of vibrators shooting at the same time as proposed by SILVERMAN [1979] in his pioneer work. Because data quality should not be significantly affected by the technique used to speed up acquisition, signal processing methods have been developed to separate simultaneously acquired shot gathers. In this extended abstract, I describe the principles and the features of the most promising of these methods.

* Schlumberger Cambridge Research, High Cross-Madingley Road, Cambridge, CB3 0EL, U.K.

2. Harmonic noise attenuation

The strict connection between the harmonics generated by hydraulic seismic vibrators and the effectiveness of the techniques developed to efficiently acquire Vibroseis data requires mention of the techniques developed to attenuate the harmonics. The techniques considered in this section aim at attenuating the harmonics, i.e., improving the data quality, rather than enhancing acquisition efficiency.

The method proposed by SORKIN [1972] to suppress harmonics and its generalization developed by RIETSCH [1981] require several consecutive sweeps. Each of the M sweeps that compose the sequence has an initial phase differing from that of the previous one by the phase angle $2\pi/M$. The value of M depends on the maximum harmonic order that it is desired to suppress. Prior to stacking, the shot gathers must be correlated with the corresponding sweep. It can be demonstrated that harmonics up to and including the Mth are suppressed. The case M=4 is of particular interest because all the even harmonics in addition to the critical 3rd harmonic are suppressed.

3. Cascaded sweeps

The price to be paid to attenuate the harmonics using SORKIN [1972] and RIETSCH [1981] methods (often called variphase methods) is the additional acquisition time due to the required series of consecutive sweeps. However, only in some circumstances, the target depth, the maximum offset, the expected absorption and the signal-to-noise ratio require transmitting a large amount of energy to the earth's interior, and therefore several sweeps are required.

To speed up acquisition while preserving the harmonic attenuation properties, ANDERSEN [1994] proposed the so-called cascaded sweep. Andersen's method eliminates the listen time by linking or cascading a number of sweep segments. The sub-sweeps, which span the entire frequency range, are identical except for different initial phases. The initial phase angles of consecutive sweeps increment by $2\pi/M$, where M is the number of sweep segments. The listen time is added only after the last sweep segment. In Andersen's method, the correlation sweep has an additional segment whose phase and position in the cascaded sweep are chosen to eliminate harmonics up to a certain order that depends on M.

4. Simultaneous shooting

Separation by phase encoding.

SILVERMAN [1979] is credited with the original idea and the first method developed to separate shot gathers obtained after simultaneous shooting. If the sweep length required at each source location is T and the listen time is L, the sequential acquisition from two locations would require (ignoring the reset time) a total time of $2(T+L)$. In Silverman's method (2×2 scheme), two consecutive sweeps of length $T/2$ are shot from two locations simultaneously, giving a total acquisition time of $2(T/2+L)$. If L is much smaller than T, the method yields an efficiency improvement of almost 50%. The 2×2 method requires the combination of a shot gather obtained with two vibrators sweeping in phase at two locations and a shot gather obtained with two vibrators sweeping with opposite polarities from the same locations.

With the 2×2 scheme, the separated shot gather at the first location suffers from the contamination of all the even harmonics generated by the other vibrator. All the self-harmonics of the first shot-gather are preserved. WARD et al. [1990] proposed a 4×2 (4 sweeps at 2 vibrator locations) phase encoding scheme that eliminates the contamination of all the harmonics generated by the other vibrator. Because the 4×2 scheme does not suppress the odd self-harmonics and in particular the third harmonic, which is often energetic, WARD et al. [1990] also proposed an 8×2 scheme.

Table I summarizes the most common simultaneous phase encoding schemes, the corresponding source matrixes and the main properties. The source matrixes, whose elements correspond to amplitudes and initial phases of the reference sweeps for a single frequency, assume that each individual vibrator can repeat its sweep except for the desired different initial phase. The summarized properties of these methods are also valid if the vibrators emit different sweeps at the different locations (e.g., s_1 different than s_2 in the 2×2 scheme). The separation of the shot gathers can be obtained by multiplying the recorded gathers by the inverse (or pseudo-inverse for rectangular matrixes) of the source matrix. The properties of the schemes in Table I can be derived by elevating each element of the source matrix to the order of the harmonic under consideration and performing the shot-gather separation. It should be noted that the higher-order schemes in

Scheme	Attenuated self harmonics	Harmonic leakage	Scheme	Attenuated self harmonics	Harmonic leakage
$2\times 2: S=\begin{bmatrix} s_1 & s_2 \\ s_1 & s_2 \end{bmatrix}$	None for the first shot gather*	Even harmonics	$8\times 2: S^T=\begin{bmatrix} s_1 & s_1e^{i\varphi} & s_1e^{i2\varphi} & s_1e^{i3\varphi} & s_1e^{i4\varphi} & s_1e^{i5\varphi} & s_1e^{i6\varphi} & s_1e^{i7\varphi} \\ s_2e^{i7\varphi} & s_2e^{i6\varphi} & s_2e^{i5\varphi} & s_2e^{i4\varphi} & s_2e^{i3\varphi} & s_2e^{i2\varphi} & s_2e^{i1\varphi} & s_2 \end{bmatrix}, \varphi=\frac{\pi}{4}$	Up to the 8th	The 7th is the first harmonic that leaks
$4\times 2: S^T=\begin{bmatrix} s_1 & s_1 & -s_1 & s_1 \\ s_2 & -s_2 & s_2 & s_2 \end{bmatrix}$	All even harmonics	None	$5\times 2: S^T=\begin{bmatrix} s_1 & s_1e^{i2\varphi} & s_1e^{i4\varphi} & s_1e^{i\varphi} & s_1e^{i3\varphi} \\ s_2 & s_2e^{i3\varphi} & s_2e^{i\varphi} & s_2e^{i4\varphi} & s_2e^{i2\varphi} \end{bmatrix}, \varphi=\frac{2\pi}{5}$	Up to the 5th.	The 4th is the first harmonic that leaks
$4\times 3: S=\begin{bmatrix} s_1 & s_2 & s_3 \\ -s_1 & s_2 & -s_3 \\ s_1 & -s_2 & s_3 \\ -s_1 & -s_2 & s_3 \end{bmatrix}$	All even harmonics	None	$4\times 4: S=\begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ s_1 & -s_2 & s_3 & -s_4 \\ s_1 & s_2 & -s_3 & -s_4 \\ s_1 & -s_2 & -s_3 & s_4 \end{bmatrix}$	None for the first shot gather*.	All the even harmonics leak to the first shot gather

Table 1. Source matrixes and main properties of the most common simultaneous acquisition schemes
*Even harmonics of the other shot gathers are attenuated

1. táblázat. Forrás mátrixok és a legáltalánosabb rengéskeltési sémák fő tulajdonságai. *A másik adatgyűjtő páros harmonikusai csillapodnak

Table I were developed for sweep lengths larger than those typically required with modern powerful vibrators and for finer receiver sampling.

MARTIN [1993] conducted a comprehensive set of experiments to assess the capability of simultaneous shooting methods to separate shot gathers and to suppress harmonics in practical conditions and concluded that the Vibroseis systems (electronics and mechanics) available in the early 90 s would permit approximately 30 dB of separation for the 2×2, 4×2 and 8×2 schemes. Because the dynamic range of the processing algorithms used to enhance the signal-to-noise ratio is often more than 30 dB, these schemes were not considered adequate.

HFVS separation

The High-fidelity-vibratory-seismic (HFVS) [ALLEN et al. 1998] method for acquiring seismic data is based on the principle that, in a Vibroseis survey, the far-field signature can be estimated from measurements made at the vibrator. These measurements, which include harmonics, are used to perform a multi-channel deterministic deconvolution of the simultaneously acquired gathers. The elements of the source matrix in this method are the estimated far-field signatures. The different initial phases of the sweeps are designed to obtain an invertible source matrix. If the assumptions made in this method are satisfied, this method achieves two objectives: shot gather separation and source signature deconvolution.

5. Slip sweep

Slip sweep is a Vibroseis acquisition method that was introduced by ROZEMOND [1996]. This method essentially consists of a vibrator group sweeping without waiting for the previous group's sweep to terminate. In the absence of harmonic noise, and if the time interval between consecutive sweeps (slip time) is larger than the listen time, the responses of the earth to consecutive sweeps do not overlap in the time–frequency domain as shown by the dotted area in *Fig. 1*. In the presence of harmonic noise, the responses may overlap as shown by the dashed area in Fig. 1, where only the earth's response to harmonics up to the second order is shown. JEFFRYES [2002] and MEUNIER and BIANCHI [2002] developed two techniques to attenuate harmonic noise in slip sweep surveys.

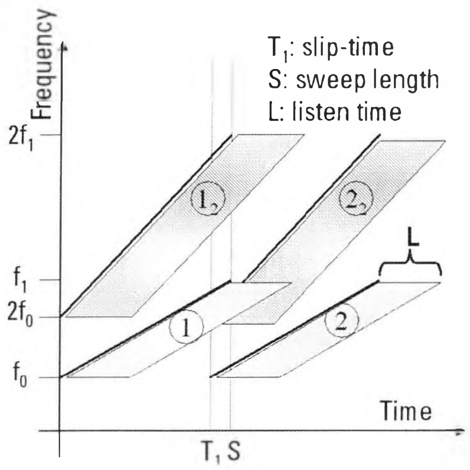

Fig. 1. Schematic representation in time–frequency domain of one trace of slip-sweep uncorrelated data obtained with two consecutive linear up-sweeps

1. ábra. Két egymást követő lineáris up-sweep-pel nyert slip-sweep korrelálatlan adatai egy csatornájának sematikus képe idő–frekvencia tartományban

6. Combination of methods

MOERIG et al. [2002] developed the simultaneous cascaded sweep method to increase the efficiency of Vibroseis acquisitions and to obtain deterministic attenuation of harmonic noise. This elegant method permits the use of cascaded sweeps during a simultaneous acquisition. The initial phases of the sweep segments that compose the cascaded sweeps are selected according to the EDINGTON and KHAN [1989] scheme and do not have to be progressively rotated by $2\pi/M$ as required in ANDERSEN [(1994].

The simultaneous slip-sweep method proposed by JEFFRYES [2002] consists of grouping the available vibrators in two or more sets and performs slip-sweep shooting between the sets of vibrators. Separation of the shot gathers within a group is obtained by simultaneous shooting with different initial phases. If, for example, two sets (A and B) of vibrators are used, at least three simultaneous sweeps per set are needed. The acquisition sequence could be A_1-B_1-A_2-B_2-A_3-B_3, in which the elapsed time between A_i, B_i and A_{i+1} is the slip time.

HUFFORD et al. [2003] also proposed to group the available vibrators in sets. The difference between this proposal and that of JEFFRYES [2002] is that the separation of the shot gathers within a set is done using HFVS deconvolution rather than simultaneous phase encoding.

7. Practical considerations

What is the best-performing efficient Vibroseis acquisition method that preserves data quality? Two key parameters dictate the effectiveness and the capability to preserve data quality of the methods described in this extended abstract: source signature repeatability and magnitude of the generated harmonics. For a given source effort, the relative importance of these two parameters along with the effectiveness of the processing methods used to compensate for the lack of source repeatability and/or energetic harmonics determine the most suitable method. The described features and assumptions of these methods lead to the qualitative classification in *Fig. 2*, where the most promising method for a given combination of parameters is indicated.

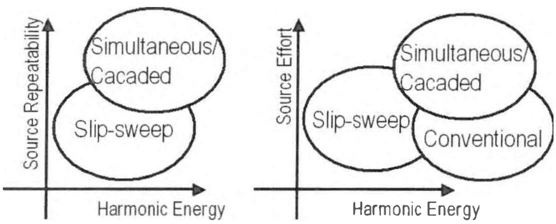

Fig. 2. Qualitative selection of the best performing efficient Vibroseis acquisition method

2. ábra. A leghatékonyabb viborszeiz módszer minőségi kiválasztása

In the case of high source signature repeatability, the deterministic cancellation of the harmonics given by the simultaneous shooting techniques is appealing and, particularly if a substantial source effort is required, simultaneous shooting techniques should be considered. If source repeatability is not satisfactory, the effectiveness of the data processing techniques to compensate for it should be assessed before considering these methods. If the harmonic noise contamination is weak compared to the response of the target reflectors to the fundamental energy, or the method to attenuate it is effective, slip sweep techniques should be considered. For short sweeps, non-repeatable source signatures and strong harmonic noise, conventional shooting may be the only viable approach.

8. Conclusions

Many methods have been developed in the past 25 years to speed up Vibroseis acquisition. I have given an overview of the most promising ones and proposed a classification of them in three categories: simultaneous shooting, cascaded sweep and slip sweeps. The main features of these methods and some combinations of them have been summarized and some criteria for the selection of most suitable one have been listed. Examples of datasets acquired with the described methods are presented.

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A hatékony viborszeiz módszerek áttekintése

Claudio BAGAINI

A vibroszeiz mérési módszer felgyorsítására sok módszert fejlesztettek ki az utóbbi 25 évben. A leginkább perspektivikus módszerekről egy áttekintést adok és javaslatot teszek felosztásukra, mely három kategóriából áll: szimultán rezgéskeltés, összefűzött vibrojelek és elcsúsztatott vibrojelek. Ezen módszerek legfontosabb jellemzői kerülnek összefoglalásra és bevezetésre kerül néhány kritérium a legalkalmasabb módszer kiválasztására.