Noise Reduction in VibroSeis Source

Kaëlig Castor, Thomas Bianchi, Olivier Winter, Thierry Klein, CGG*

Summary

Vibroseis production rates are often limited by inter-record harmonic–noise contamination. Whereas this problem is often handled during seismic data processing, this paper presents a noise-reduction method that applies on the source itself. The basic principle is to measure the output noise and to inject adaptively the opposite signal in the source input to converge towards an ideal output. This new method is under patent application and shows efficient results for minimizing distortion noise from a seismic vibrator.

Introduction

Seismic vibrators display intrinsically a nonlinear behavior mainly related to the nonlinear characteristics of the hydraulic servo-valve and to the nonlinear mechanical properties of the baseplate-ground contact (Sallas, 1984). Servomechanism electronics aims to deliver a perfect match on phase and fundamental amplitude between input and output signals. Even if the nonlinear behavior of the seismic source is accounted for in the electronics (Boucard, 2010), some significant ground-force distortion noise remains and is a limiting factor in vibroseis acquisition since it propagates into the soil. After correlation, the harmonic noise generated from an upsweep is confined in the negative time. The classical flip-flop technique consists in shooting sequentially two or more sources with the waiting time between each shot chosen to prevent any harmonic noise pollution between successive shots. To increase shot-productivity, the so-called slip sweep method (Rozemond, 1996) consists in reducing the time between successive shots so-called slip time. In this case, the harmonic-noise contamination from one shot to another has to be handled.

Some efforts have been made to treat the harmonic distortion problem in different ways, for example, by stacking successive shots with phase-rotated sweeps (Shrodt, 1987). Contamination of correlated vibroseis records by harmonic energy generated by subsequent sweeps in slip-sweep technique has been overcome by various approaches. The source-noise reduction has often been performed directly on the correlated seismic data with a specific processing such as time-frequency diversity stacking (Ras, 1999) or single-value decomposition (Jianjun, 2012). A method named HPVA (High Productivity Vibroseis Acquisition) was developed to remove the harmonic noise from the correlated seismic data (Meunier, 2002, Meunier, 2005). Some attempts have been made to reduce the harmonic noise directly at the source or at least some models have been developed to apprehend the nonlinear phenomena. Lebedev *et al.* developed a nonlinear contact-rigidity model of the nonlinear source in addition to the primary distortion generated by the hydraulics (Lebedev, 2004, Lebedev, 2006) in order to improve the model of the ground force estimation.

With recent advances in vibroseis acquisition, a focus on low frequency in the source has emerged with adapted low-dwell sweeps (Bagaini, 2007, Sallas, 2010). However, the noise source has remained an issue, especially at low frequency where the drive is low. As harmonic distortion noise energy is high at low frequency, and weakly attenuated, it is highly desirable to attenuate it at the emission.

Method and Results on Ground Force

The harmonic-noise reduction technique proposed in this paper is based on a learning process. It consists in measuring the noise in the output reaction-mass and baseplate acceleration signals and to re-inject it as an anti-noise signal in the input pilot signal without any change on the fundamental component. This noise cancellation is well-known as active noise control in classical actuator

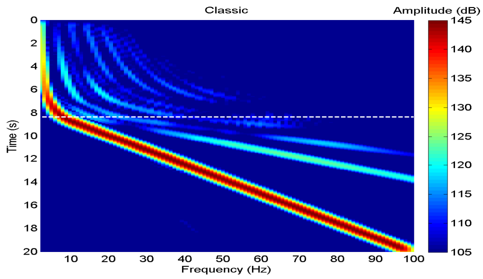

Figure 1a

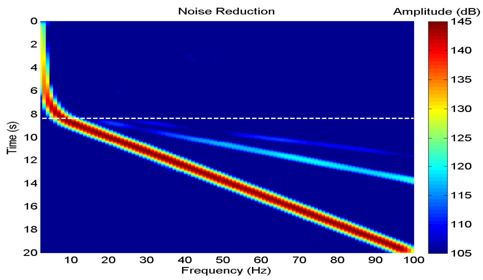

Figure 1b

Figure 1: Time-frequency represention of the averaged ground force with classic (Fig. 1a) and noise-reduction (Fig. 1b) sweeps where 15 harmonics are processed. The white dashed line delimits the noiseless zone

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control design. The noise reduction works on the repetitive part of the harmonic distortion. Figure 1 shows the efficiency of the noise reduction method especially at low frequency, on an averaged time-frequency representation of ground forces measured at different locations for a single 60000-lbf vibrator. At low frequency, below 10Hz, the noise is strongly minimized. At higher frequency, the observed noise-reduction is respectively about 40% and 60% for the first and second harmonics. Figure 2 exhibits the noise reduction on the total distortion versus time.

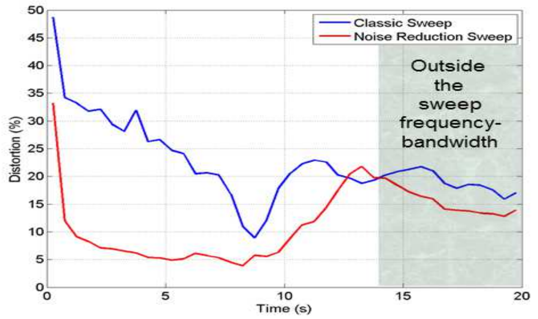

Figure 2: Total distortion for classic and noise-reduction sweeps with 40 harmonics processed.

At low frequency, the maximum force is limited by the reaction-mass displacement. The harmonic distortion, due to its triangular wave shaping (Fig. 3b), could be interpreted as a key factor that limit the vibrator force output (Wei, 2013). From the proposed harmonic reduction method, particularly efficient at low frequency, the resulting ground force displays clearly a more sinusoidal time-waveform (Fig. 3b) and a more regular and less noisy ground-force envelope (Fig. 3c and 3a). However, the measured reaction-mass displacement is higher than in a classical sweep. Consequently, it should not allow increasing the drive for the low-frequency range.

Effect on Seismic Data

A slip-sweep acquisition test with three 60000-lbf vibrators has been done with the classical 20s- [2-100Hz] low-dwell sweep and with the harmonic reduction method as presented in Fig. 1-3. We used a 5s- record length and a 5s-slip-time. Figure 4b with harmonic-noise reduction displays a clearly cleaner record than Figure 4a with a classical source. “Self-harmonic noise” (top blue arrows) and next-shot noise (bottom green arrows) are both diminished. Figures 4c and 4d show the same data with a low-pass filter at 15Hz and a +12dB/oct. geophone frequency-response compensation filter with a 10Hz- cutoff frequency. Some reflections can be directly identified at 1.25s with the source-noise reduction which is barely the case with the classical acquisition.

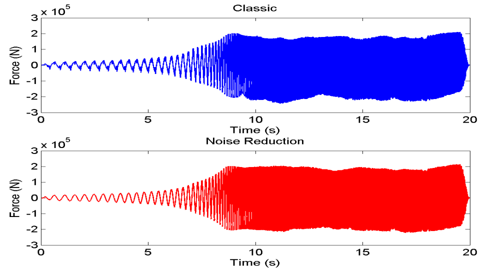

Figure 3a

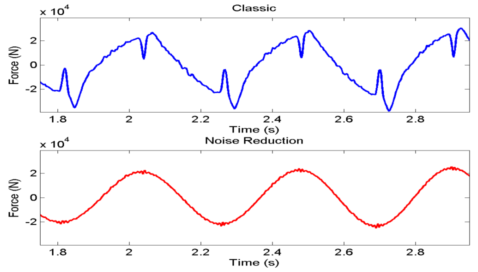

Figure 3b

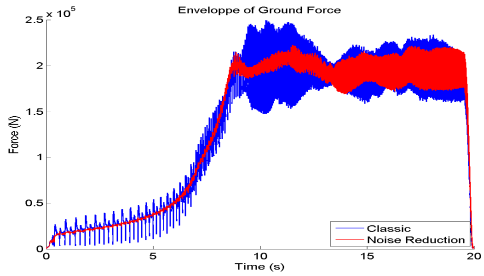

Figure 3c

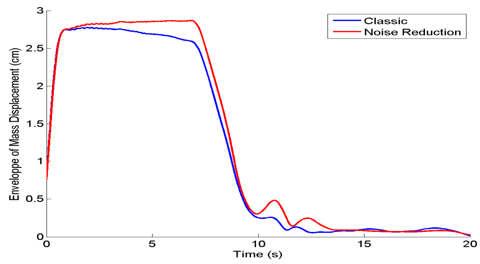

Figure 3d

Figure 3: Time waveforms (Fig. 3a and zoomed around 2.5Hz in Fig. 3b) and envelopes (Fig. 3c) of averaged ground forces, and associated envelope of reaction mass-displacement (Fig. 3d) for classic and noise-reduction sweeps

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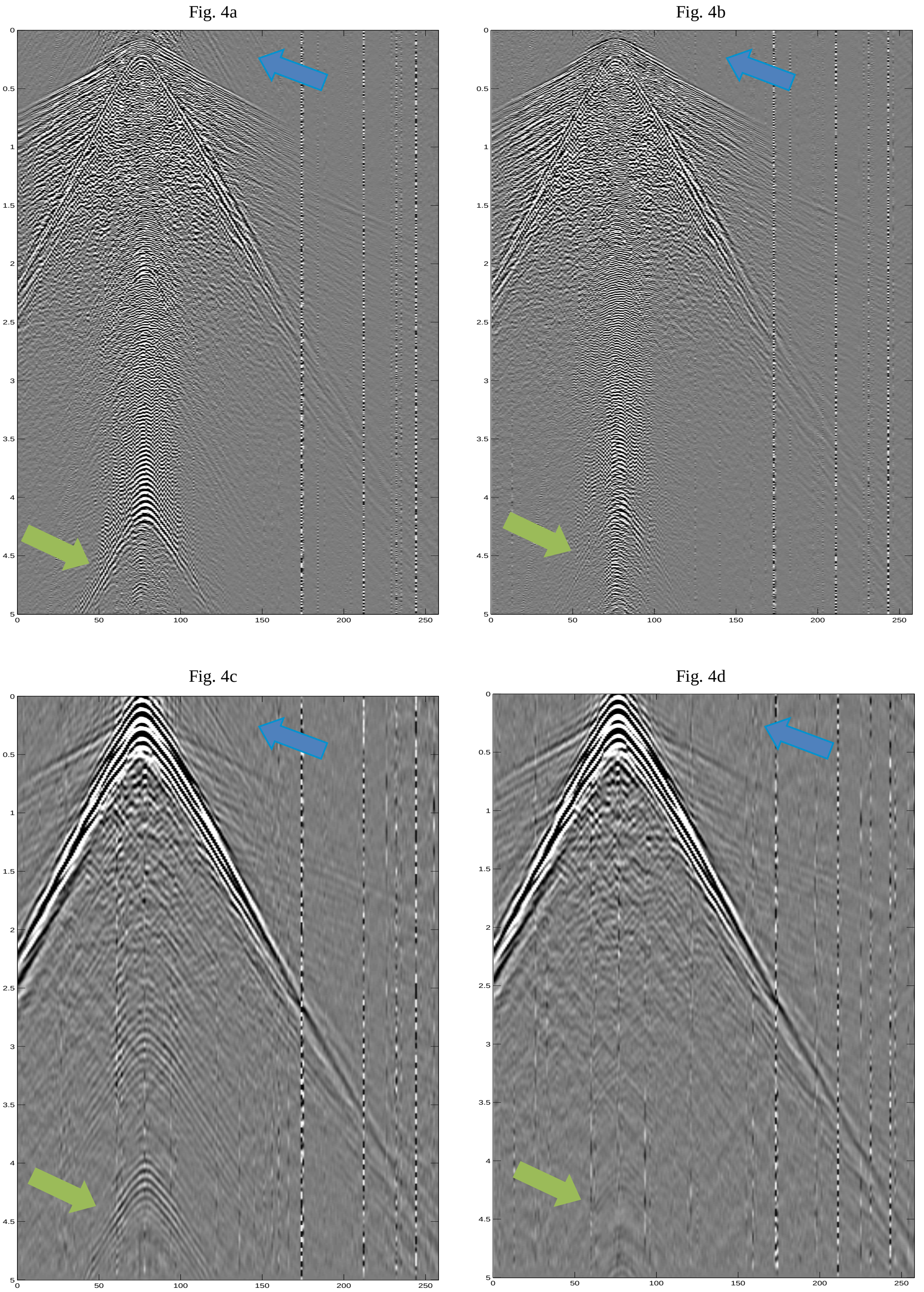

Figure 4: Slip-sweep shotpoints for classic (Fig. 4a) and noise-reduction (Fig. 4b) sweeps. A 15Hz- low-pass filter is applied in Fig. 4c and 4d. Harmonic distortion from current shot ("self-harmonic noise", present in slip-sweep or flip-flop acquisitions) is flagged by the blue arrows whereas harmonics from next shot ("cross-harmonic noise", present only in slip-sweep acquisition) is flagged by green arrows.

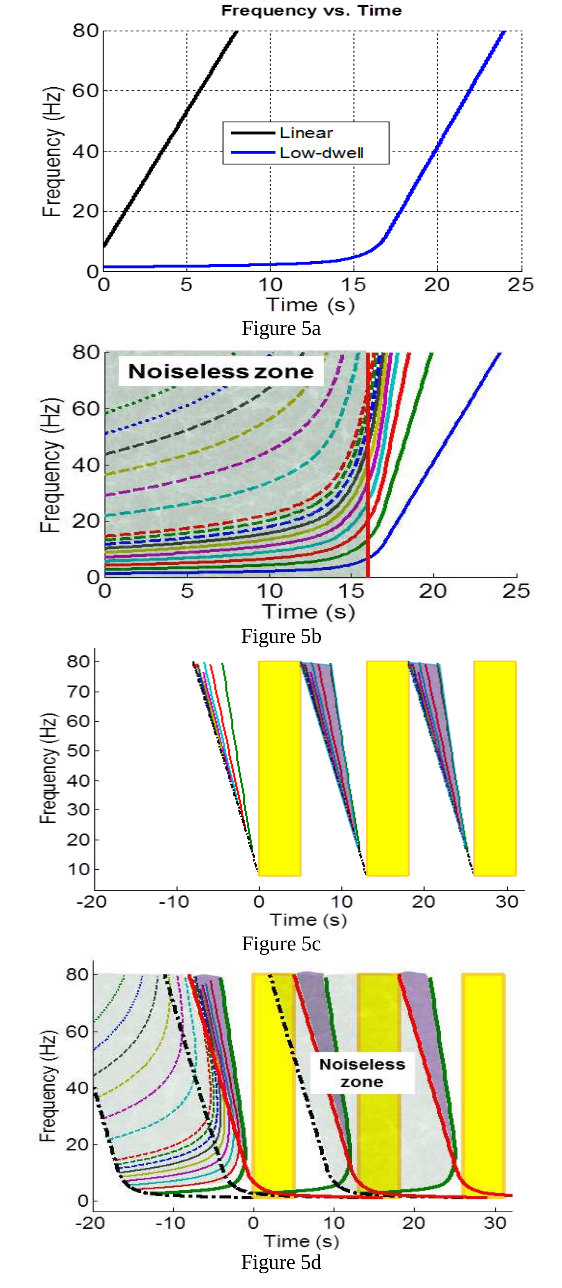

Figure 5: Example of comparison beween a low-dwell sweep and its equivalent linear sweep with the same sweep rate. Fig. 5a shows the instantaneous frequency. Time-frequency repartition of harmonic-noise are shown before correlation for the single low-dwell sweep including its noiseless zone from our method (Fig. 5b) and after correlation for three slip-sweep records in case of the linear sweep (Fig. 5c) and the low-dwell sweep (Fig. 5d). Yellow boxes map listening time. The harmonic-noise zone boundaries for each shot is defined by a thick black dashed line corresponding to the infinite order harmonic and a thick green line corresponding to the second harmonic. The noiseless zone is delimited by the thick red line corresponding to the harmonics generated by a low-frequency fundamental up to 16s (Fig. 5b and 5d).

Acquisition Quality and Productivity Benefits

Reducing perfectly the source-noise where the fundamental component is low-frequency deliver value to enlarge the frequency bandwidth without increasing time constraint between successive shots. Figures 5 show a comparison between a [1.5-80Hz] 24s low-dwell sweep and a [8-80Hz] 8s linear sweep with the same sweep rate in the common frequency bandwidth to get the same seismic energy (Fig. 5a). We simulate a slip-sweep acquisition with a 5s-listening time, a 13s-slip time, and show the corresponding harmonic noise location for three correlated shots. Figure 5b displays the harmonics for a low-dwell sweep including the noiseless zone reached with our method. In the slip-sweep simulation, the fundamental components of the three shots are respectively at t=0, 13s and 26s (Fig. 5c and 5d). For the linear sweep case (Fig. 5c), the acquisition is a flip-flop acquisition since there is no harmonic noise contamination from one shot to the previous one. Figure 5d exhibits the harmonic-noise location when the low-dwell sweep is used. In this last case, the addition of the 16s- low-frequency vibration in the [1.5-8Hz] bandwidth (Fig. 5a), due to the very low sweep-rate, leads to the significant spreading of the harmonic-noise contamination zone in the time-frequency domain (Fig. 5d) but the noise-reduction gives an equivalent result to the flip-flop with linear sweep.

Finally, the low-frequency source noise reduction presents two possible advantages for improving seismic acquisition. On one hand, for a given low-dwell sweep we expect a gain of productivity. The noise reduction permits to decrease the time between successive shots by considering the low-frequency noiseless zone in the correlated time-frequency domain. On the other hand, for a classical flip-flop acquisition with a linear sweep, the source-noise reduction can improve the quality of data extending the frequency bandwidth by more than two octaves. By using a low-dwell sweep, we have only a low extra-cost in shooting time but no waste in time between successive shots.

Conclusion

An efficient noise-reduction method for vibroseis source under patent application is presented in this paper. The particularly good results obtained at low frequency allow reducing slip-time with some specific low-dwell sweep design in slip-sweep acquisition, or at least, slip-sweep can be used instead of flip-flop acquisition with an expected productivity improvement for a same quality of data.

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EDITED REFERENCES

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