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Efficient Harmonic-Distortion Mitigation on Vibro-Seismic Sources

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SUMMARY

In seismic land acquisition, harmonic–noise in vibrator ground-force has always been a major limitation in terms of data quality and productivity. In high productivity acquisition, vibrator distortion is usually prevented by waiting enough time between successive shots. Otherwise, it has to be reduced during seismic data processing.

The low-dwell sweeps that are now currently used in production can induce even more important distortion issues. Harmonics from low frequency content can be considerably more spread out over time after correlation. Consequently, the extensive use of the low-frequency bandwidth for vibro-seismic sources prompted the need for improved distortion control, especially at low frequency.

This paper describes a method to mitigate the harmonic distortion directly before emission. The output noise is measured and injected adaptively with opposite phase in the source input to converge towards an ideal output. The results show important noise reduction over the full bandwidth, with perfect low-frequency fidelity. A better source signal quality provides better seismic data that is easier to process, and opens new possibilities in terms of acquisition scenarios with possible productivity improvement.

Introduction

Hydraulic and mechanical behaviors are well-known to be nonlinear in vibro-seismic sources (Sallas, 1984). Consequently, the seismic energy delivered by such a system exhibits a classical noise footprint in addition to the desired force source signature applied to the ground. Harmonic distortion has always been one of the most important vibro-seismic source constraints in terms of data quality and productivity in seismic land acquisition. The vibrator servomechanism generally provides an efficient match on fundamental amplitude and phase between input and output signals. However, while vibrator nonlinearity models are included in the vibrator electronic controller to generate a nonlinear input that reduces harmonic distortion (Boucard, 2010), significant noise remains in the estimated ground force signature. A seismic survey usually adapts itself to the source noise limitations, and it is important to notice that due to high distortion in the generated ground force quality control, vibrators can often be stopped and removed from production, and reshooting can be requested. Historically, the harmonic noise was handled by the use of an upsweep source signal to concentrate the noise pollution in the negative time and prevent any noise in a single correlated record. For production, classical flip-flop acquisition was designed to manage sequential shooting with a waiting time between each source which avoids noise contamination on one shot from the next shot harmonics. To reach higher productivity, the time between successive shots, the so-called slip time, was then reduced in the slip-sweep acquisition method (Rozemond, 1996). Reducing the resulting harmonic noise pollution was attempted either with acquisition methods such as phase-rotated sweep stacks (Shrodt, 1987) or during correlated-record processing by using time-frequency diversity stacking (Ras, 1999) or single-value decomposition (Jianjun, 2012). For many years, a processing method named HPVA (High Productivity Vibroseis Acquisition) has been used extensively in slip-sweep acquisition to remove harmonic noise post-acquisition (Meunier, 2002). Further work has been done to reduce the harmonic noise directly at the source, and some models have been developed to understand 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) to improve the ground force estimation model. Numerous achievements have been recently made regarding the sweep definition that can be customized to fit the vibrator physical limitations with maximum efficiency. Adapted low-dwell sweep design (Bagaini, 2007) allowed broadband seismic advances. However, harmonic distortion has remained an issue, especially at low frequency where the drive is low. A need for addressing harmonic-noise reduction in the vibrator before emission has emerged.

Harmonic-Noise Reduction on Ground-Force

To clean-up the ground force in terms of harmonic noise, the proposed method in this paper is a noise-cancellation algorithm. The fundamental principle is well-known as active noise control in a classical actuator control design. Based on a learning process, the noise-reduction method is most efficient on the repetitive part of the harmonic distortion. Its original approach relates to an accurate signal-processing algorithm based on the phase cancellation principle with no need for a complex modeling of vibrator hydraulic and mechanical behavior: it consists in measuring the noise in the output reaction-mass and baseplate acceleration signals and re-injecting it as an anti-noise signal in the input pilot signal. Careful attention is given to preserve the fundamental component of the input signal which is the useful signal for seismic data acquisition. The results on the estimated ground force show important noise removal. Figure 1 represents the averaged time-frequency plot of the ground forces measured at different locations for a single 60000-lbf vibrator with a 20s- [2-100Hz] low-dwell sweep. 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 2a shows that the total harmonic distortion of the ground force is considerably lowered with the proposed method. The noise-reduction is particularly noticeable at low frequency on the time waveform (Fig. 2b): the classical triangular saw tooth profile of the ground force (Fig. 2b) turns out to be almost sinusoidal after noise reduction.

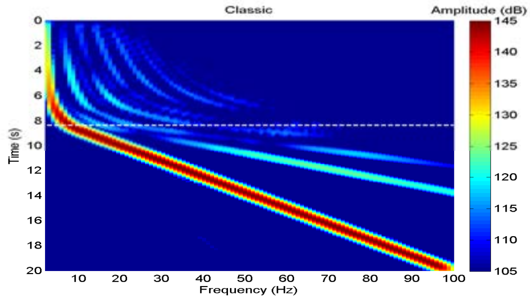

Fig. 1a

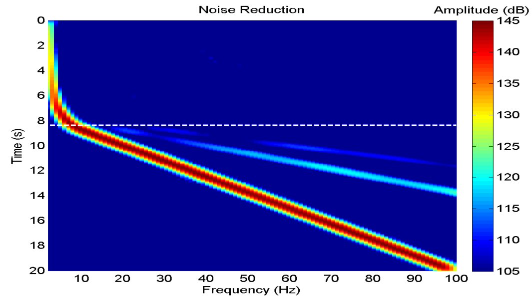

Fig. 1b

Figure 1 *Time-frequency representation of the average ground-force with a classical 20s- [2-100Hz] low-dwell sweep (Fig. 1a) and with the noise-reduction method (Fig. 1b). The white dashed line delimits the low-frequency noiseless zone obtained with noise-reduction method.*

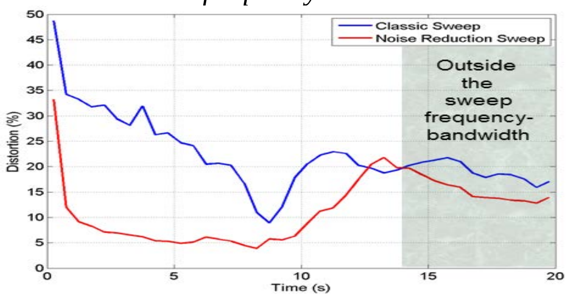

Fig. 2a

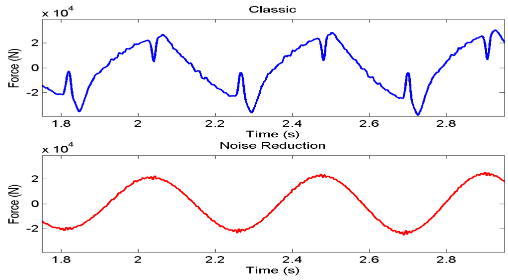

Fig. 2b

Figure 2 *Average ground-force noise-reduction results on total harmonic distortion (Fig. 2a) and time-signal zoomed around 2.5Hz (Fig. 2b) for classic (blue) and noise-reduction (red) sweeps.*

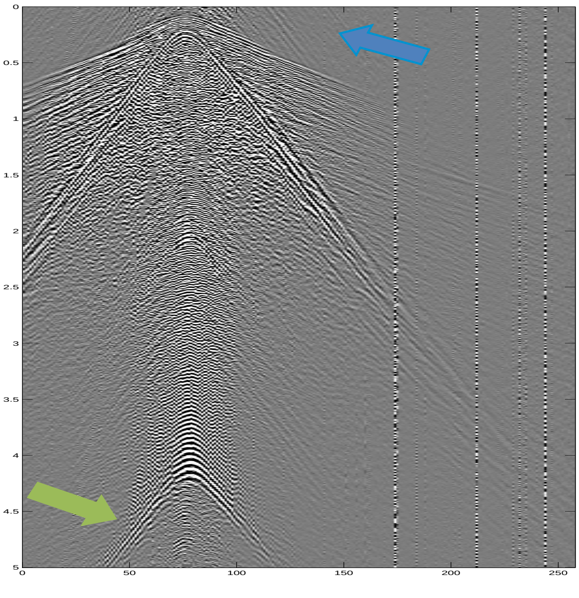

Fig. 3a

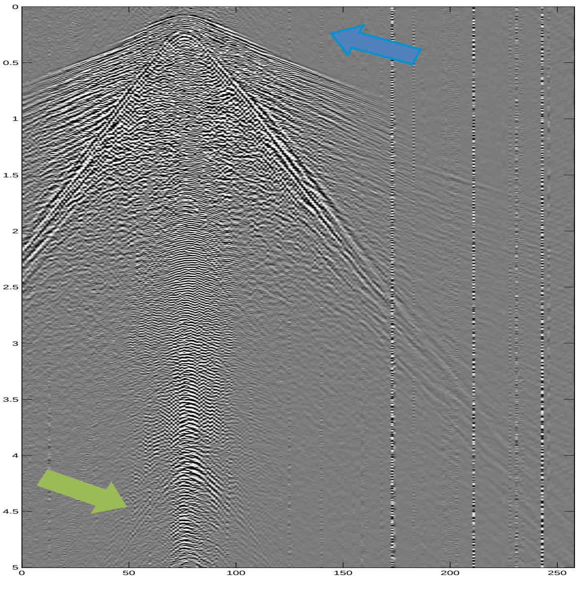

Fig. 3b

Figure 3 *Slip-sweep shotpoints for classic (Fig. 3a) and noise-reduction (Fig. 3b) sweeps. 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.*

Effects of Source-Noise Reduction on Seismic Data

With a 20s- [2-100Hz] low-dwell sweep, a slip-sweep acquisition test with two fleets of three 60000-lbf vibrators was performed using the harmonic-reduction method. A 5s- record length and a 5s- slip-time were used. Figure 3b with harmonic-noise reduction displays a cleaner record than Figure 3a with a classical source regarding the "self-harmonic noise" (top blue arrows) and the next-shot noise (bottom green arrows). Figure 4 shows the same dataset with a low-pass filter at 15Hz and a +12dB/oct. geophone frequency-response compensation filter with a 10Hz- cutoff frequency. A red dashed line in the lower panel of Figure 4 points out some reflections that can be identified at 1.25s with the source-noise reduction. Furthermore, if the ground-force low-frequency noise is not emitted, seismic data processing will be easier. In particular, a clean first-break is obtained that especially facilitates full waveform inversion. Figure 5 shows shot gathers ordered by increasing offsets where first arrivals are cleaned up with the noise-reduction method. A better wavelet can then be obtained for inversion processes. Besides the direct data quality and the processing benefits, emitting perfectly clean low frequency opens new acquisition scenarios such as the possible use of down sweeps or dedicated vibrator fleets per bandwidth. In this latter scenario, the vibrators dedicated to the low-frequency band would not pollute the high-frequency band. Finally, one of the main opportunities offered by this technology is to improve productivity by reducing the slip-time while shooting very low frequency. For specific low-dwell sweeps starting at very low frequency, the noise reduction allows us to decrease the time between successive shots by taking into account the low frequency noiseless zone (Fig. 1) in the correlated time-frequency domain. It is also possible to extend the frequency bandwidth by more than two octaves in a classical acquisition where no low-dwell is used with only a small extra-cost in shooting time but no waste in time between successive shots.

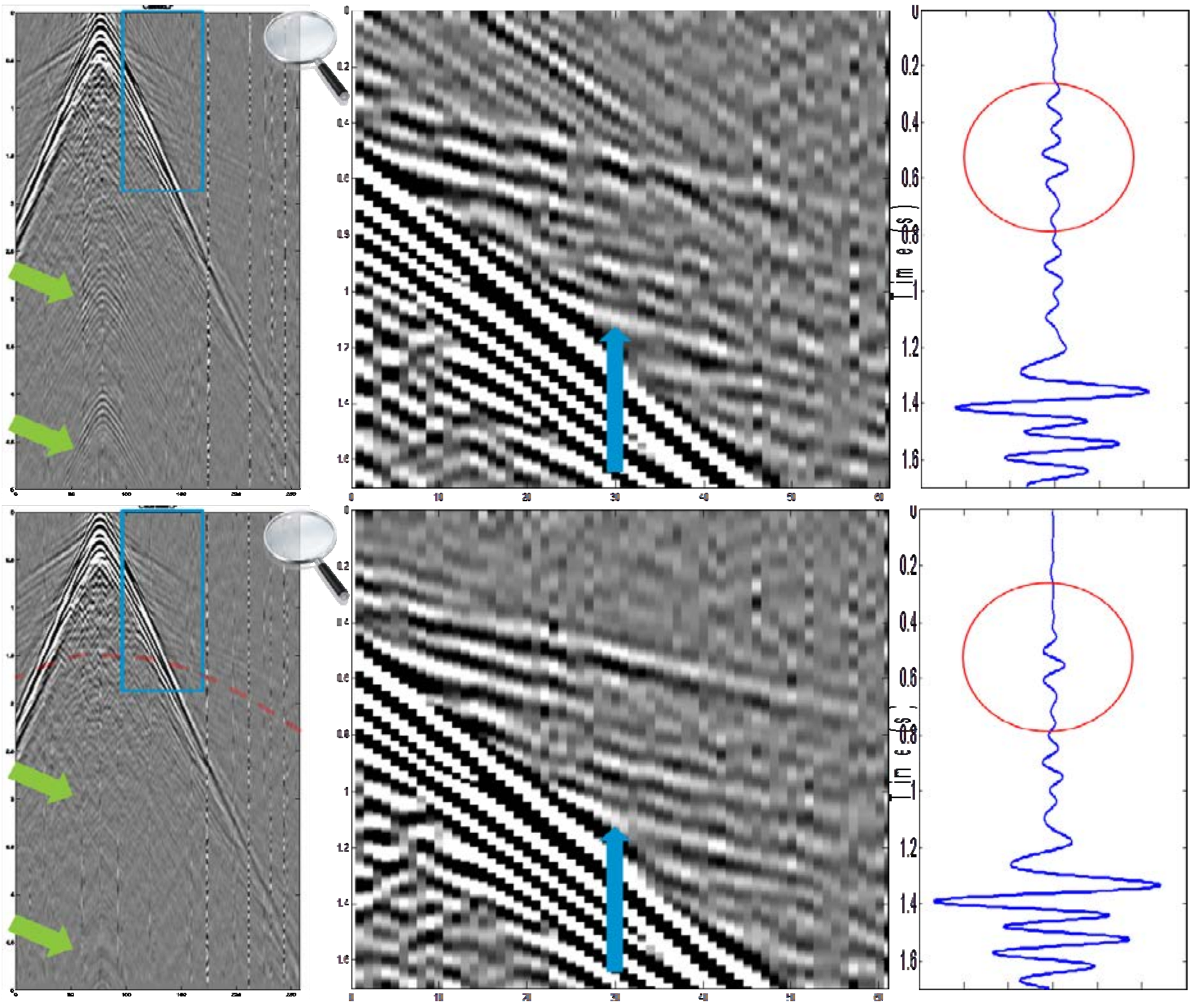

Figure 4 *Slip-sweep shotpoints for classic (left-upper panel) and noise-reduction (left-lower panel) sweeps after applying a 15Hz- low-pass filter to Fig.3 shotpoints. Green arrows show the cross-harmonic-noise. The red-dashed line (left-lower panel) displays much clearer reflection events due to noise-reduction sweep. The central panels zoom in on the first arrivals where the self-harmonic noise interference pattern can be clearly identified for a classic sweep. A selected trace pointed by the blue arrow is finally shown on the right-panels where the noise-reduction sweep exhibits (red circles) cleaner first arrivals which facilitates processing, especially full-waveform inversion.*

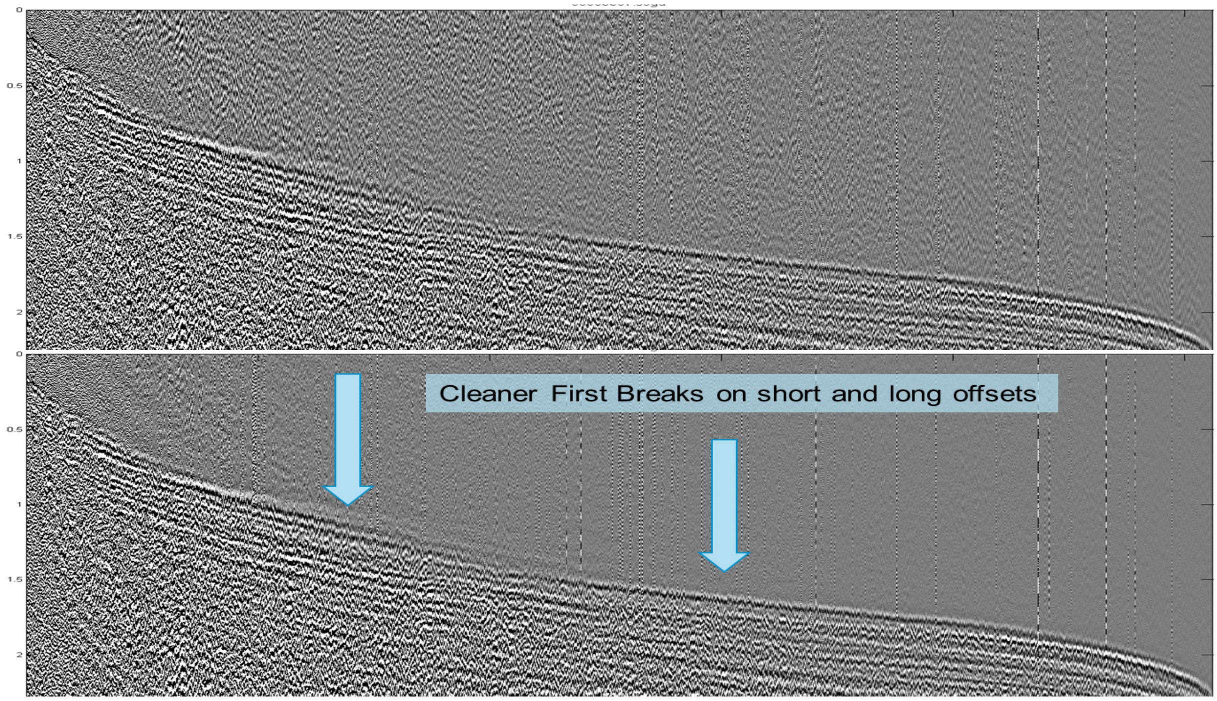

Figure 5 *Shotpoint gathers ordered by offset for classic (top) and noise-reduction (bottom) sweeps.*

Conclusion

Mitigation of ground force noise directly at the source is efficient over the full bandwidth and especially at low frequency. Beyond the better data quality obtained, the presented results open new perspectives in terms of acquisition and productivity. Reproducing low frequency vibro-seismic signals with high fidelity gives us the opportunity to reduce the slip-time with specific low-dwell sweep design in slip-sweep acquisition or, at least, to use slip-sweep instead of flip-flop acquisition with an expected productivity improvement for the same quality of data.

Acknowledgements

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