SmartLF for robust and straightforward reduction of low-frequency distortion

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Summary

Extending the seismic signal frequency towards the low frequencies has become almost standard on Vibroseis seismic projects, owing to the benefits it provides in terms of vertical resolution, signal penetration, inversion workflow results or ease of interpretation. However, the emission of this new low-frequency bandwidth is associated with levels of distortion much higher than with the conventional sweep bandwidth, owing to the inherent design of seismic vibrators based on hydraulic actuators. Several solutions have been proposed in recent years to prevent the generation of this distortion, but their field implementation remains thus far quite restricted due to either limited performance or proprietary technologies, not commercially available to third parties. This abstract presents a new approach for reducing the low-frequency distortion, embedded in the vibrator electronics itself and easy to implement and use during seismic operations. Field tests performed with different vibrators on various terrains confirmed the efficiency of this new approach.

Introduction

Low-frequency Vibroseis has been associated since its introduction a decade ago with low-dwell sweeps (Bagaini 2007, Sallas 2010), that remain the only sweep type that allows accurate spectrum control (Tellier 2019). Vibrator output is reduced at low frequencies to fit to vibrator mechanical and hydraulic limitations and offer the shortest possible low-frequency taper duration. The low-frequency seismic signal generated has a lower amplitude than the "traditional" higher frequencies, and is associated with higher distortion owing to the vibrator system limitations. This low-frequency distortion is furthermore poorly absorbed, and represents an important source of noise on seismic records. Different methods have been proposed to handle this harmonic contamination during processing (e.g., Meunier 2002) and overcome the limitation in vibrator production rate related to inter-record harmonic noise contamination. However, it remains preferable to avoid generating this distortion directly in the field, in particular as seismic records get more and more noisy with the current industry trend for simultaneous sources and reduced source and receiver arrays, or single source, single sensor.

Foreword about harmonic distortion

Generating seismic signal with vibrators is associated with harmonic distortion that is typically distinguished between:

- Even harmonics, that are mainly due to the wave propagation in the near surface. These harmonics are attributed to a variation in propagation velocity during the compression-decompression cycle, and are then mainly ground related.
- Odd harmonics, that have their origins mainly in vibrator itself, and will then depend on the actuator design, its isolation from the truck or buggy, as well as correct hydraulic settings and maintenance.

It is worth remembering, contrary to phase and amplitude that are seismic signal QC's, distortion is mainly an equipment QC. A distortion level higher on one specific vibrator when compared to others will indicate a failure on that unit, that will require either adjustments or repairs, while high levels of distortion on all vibrators correlates generally well with terrain-related effect.

Comparing levels of distortion between different vibrator electronic models is not relevant, as different computation methods can be used. For instance, the maximum frequency selected for distortion computation may differ (and is generally not customizable by users), and the distortion computation can be based on harmonics only, or on all signal but the fundamental (the latter including both subharmonics and intra-harmonics noise).

As a remark, the position of accelerometers is also paramount for proper QC computation (force, phase and distortion) at high sweep frequencies. An accelerometer located on the actuator top plate provides apparently excellent QC, but is not representative of the true signal transmitted into the subsurface (the latter requiring tools such as a load cell bench or a VSP to be assessed). Conversely, an accelerometer located on the base plate provides QC much more representative of the down-going signal. The reliability of the QCs can always be improved by using several accelerometers at optimized base plate locations (Boucard 2010, Tellier 2015).

Distortion in low-frequency Vibroseis

Due to their very nature, seismic vibrators naturally produce levels of harmonic distortion higher in the low frequencies (typically below 5 to 10 Hz, according to the sweep and vibrator selected) than on the conventional sweep bandwidth, which has become particularly noticeable since low-dwell sweeps were introduced. This low-frequency distortion has its source mainly in the following phenomena:

- Vibrator non linearities at low frequencies (square root relationship between the oil flow and the hydraulic pressure);

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- Servo valve overlap at low frequencies (brief and sharp drop in hydraulic pressures when the servo valve passes by its neutral position);
- Non-linear mechanical properties of the baseplate-ground contact, and variable contact area during a cycle (Sallas, 1984);
- Hydraulic pressure oscillations (though significantly mitigated on modern vibrators with accumulators installed as close as possible to the servovalve);
- Resonant frequency of the airbags that isolate the seismic actuator from the truck or buggy (typically ~2 Hz);
- Friction and wear.

Existing mitigation solutions

Several distortion reduction methods have been introduced in recent years to reduce distortion at low frequencies while generating the sweep:

- On VE vibrator electronics, vibrator non linearities at low frequencies (i.e., the square root relationship between the oil flow and the hydraulic pressure) have been integrated in the vibrator model, since VE416 released in 1988 (Ollivrin 2008). To accompany the industry expectancy for ever lower frequencies (< 5 Hz), this was further improved by an accurate control of low-frequency gain and phase (Tellier 2014).

- VibPro HDR (Phillips 2010) is based on an effort to compensate the hydraulic system non-linearity and the servovalve overlap, though not specifically on the low-frequency side. All harmonics are reduced, except the second that is strengthened on the documentation published by the manufacturer (Figure 1).

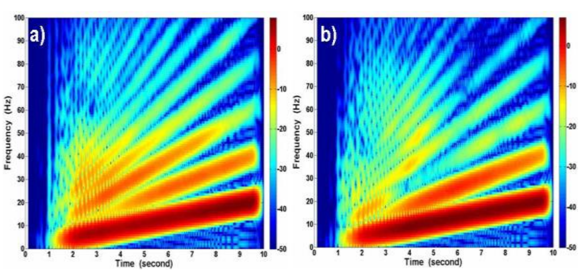

Figure 1: Comparison of the ground force with HDR Technology on and off at low frequencies from 1 Hz to 21 Hz. a) HDR Technology off. b) HDR Technology on. From manufacturer brochure.

- CleanSweep (Castor 2014) consists of adding an anti-distortion signal to the sweep pilot (180° phase shifted distortion) computed from the ground force, in an approach similar to the one used for noise-cancelling headphones. This solution is supported by the VE464 electronics, owing to the requirement for a fast servo-control able to accurately follow a more complex anti-distortion pilot. The CleanSweep technique provides excellent distortion performance at low frequencies, and addresses all ranks of harmonic noise (Figure 2).

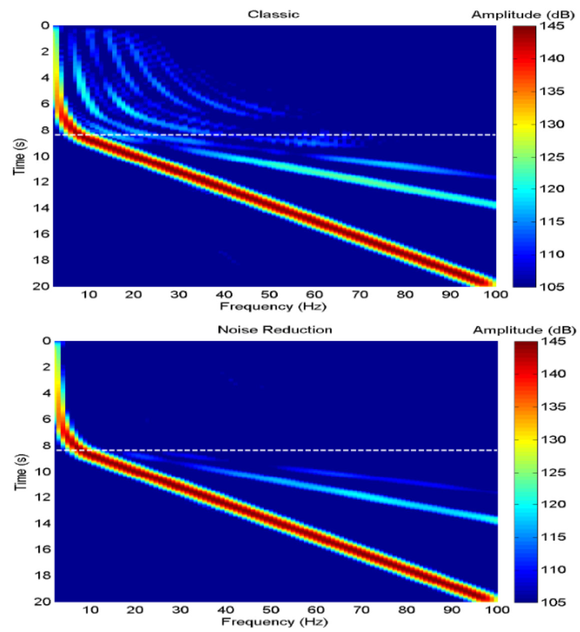

Figure 2: 1.5-100 Hz, 20 s, 60,000 lbf vibrator, without (top) and with (bottom) CleanSweep. From manufacturer brochure.

A new approach for low-frequency distortion reduction

In a new approach to overcome the limitations of previous solutions for low-frequency distortion reduction by the means of a robust, powerful and straightforward tool, the vibrator model was improved to better take into account the various sources of low-frequency distortion mentioned previously.

Based on this improved model, the servo control is able to predict the low-frequency distortion: the servo valve input signal is modified accordingly and the generation of harmonics avoided. The production pilot signal remains unchanged: the vibrator electronics models, anticipates and corrects the intrinsic behaviour of the vibrator system to guarantee a ground force as close as possible to the desired pilot, resulting in a significant reduction of distortion at low frequencies. The overall ground force signal at low frequencies is cleaner, all ranks of harmonics are reduced and most of the low-frequency, below 15 Hz, distortion is addressed (Figure 3). The robustness of the servo control is preserved, i.e., no compromises are made on phase and fundamental signal performance (Figure 4). As the production pilot signal remains unchanged, a single pilot can be used for all vibrators for the correlation process, thus reducing the complexity and chances of errors associated with vibrator-dedicated pilots.

This solution, called SmartLF and embedded in VE464 vibrator electronics, does not require modifications to the vibrators or additional mechanical components. It is easy to set up at crew start-up, without prior expertise or knowledge.

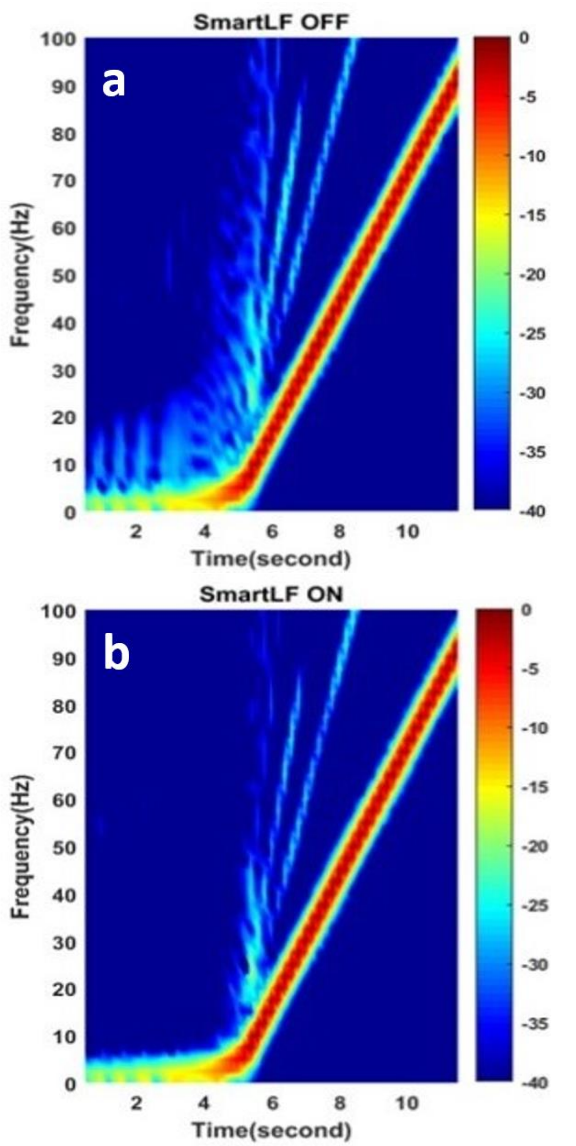

Figure 3: Low-frequency distortion results for a low-dwell sweep 2-96 Hz, 80% 12s, Nomad 65 Neo, ploughed field: (a) SmartLF off, (b) SmartLF on.

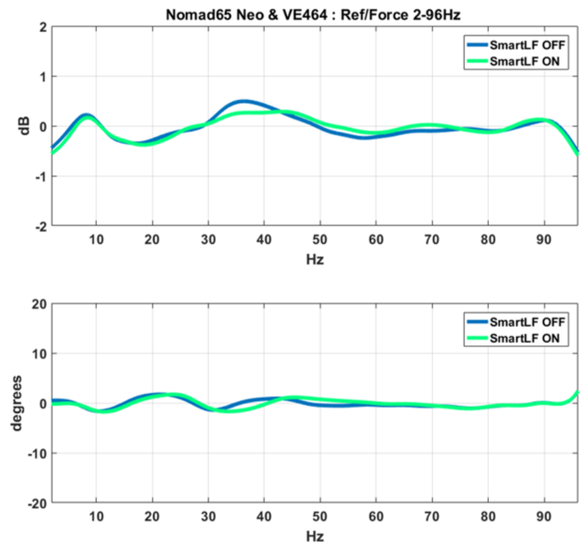

Figure 4: Comparisons between SmartLF off (blue) and on (green) shows that the solution does not influence ground force (top) and phase (bottom) vibration results.

Several field tests have demonstrated the performance of the solution on various types of vibrators: super-heavy (80,000 lbf) vibrators (Figure 5), heavy (62,000 lbf) vibrators (Figure 3), and light (16,135 lbf) vibrators (Figure 6). Good low-frequency sweep quality can be achieved with the latter, though these light vibrators are designed more for high-frequency performance (up to 400 Hz, depending on terrain) than low-frequency performance (full-drive start frequency at 7 Hz).

Conclusion

Reducing the high levels of distortion associated with low-frequency Vibroseis has become a key concern for oil and gas companies, in order to acquire high quality datasets and reduce the generation of noise directly in the field, and in particular as records acquired with simultaneous sources and single vibrators and receivers are getting more and more noisy.

A new solution integrated into the vibrator electronics has been developed, based on a robust vibrator low-frequency model that better integrates the various causes of low-frequency distortion; an advanced servo control can then predict distortion in advance and prevent its generation, with no modification of the production pilot and preservation of the sweep quality.

The solution proposed is easy to implement, with no requirement for calibration, nor additional mechanical components or particular vibrator settings. Its performance on various vibrators has been proven in the field, and deployment of the solution is at the time of the writing ongoing on commercial production projects.

Reducing the distortion even further and across all sweep frequencies, would require further innovative approaches, and could be contemplated if oil and gas operators were to confirm their interest in having near distortion-free records.

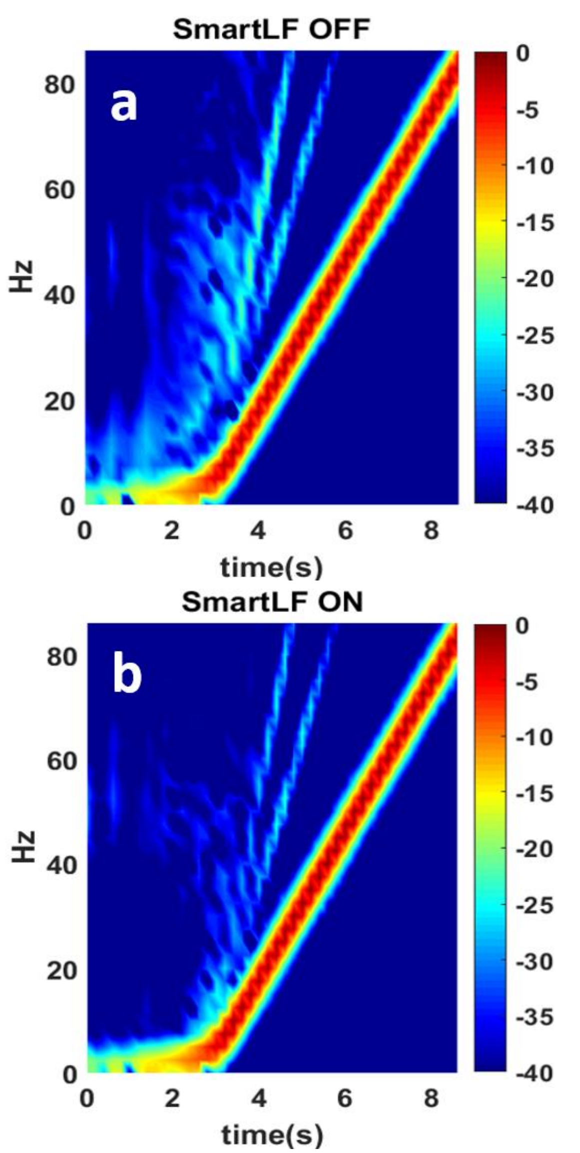

Figure 5: Low-Dwell 1.5-86 Hz, 9 s, 75 %. 80,000 lbf vibrator (Nomad 90 Neo), concrete pad, Southern France. (a) SmartLF off, (b) SmartLF on.

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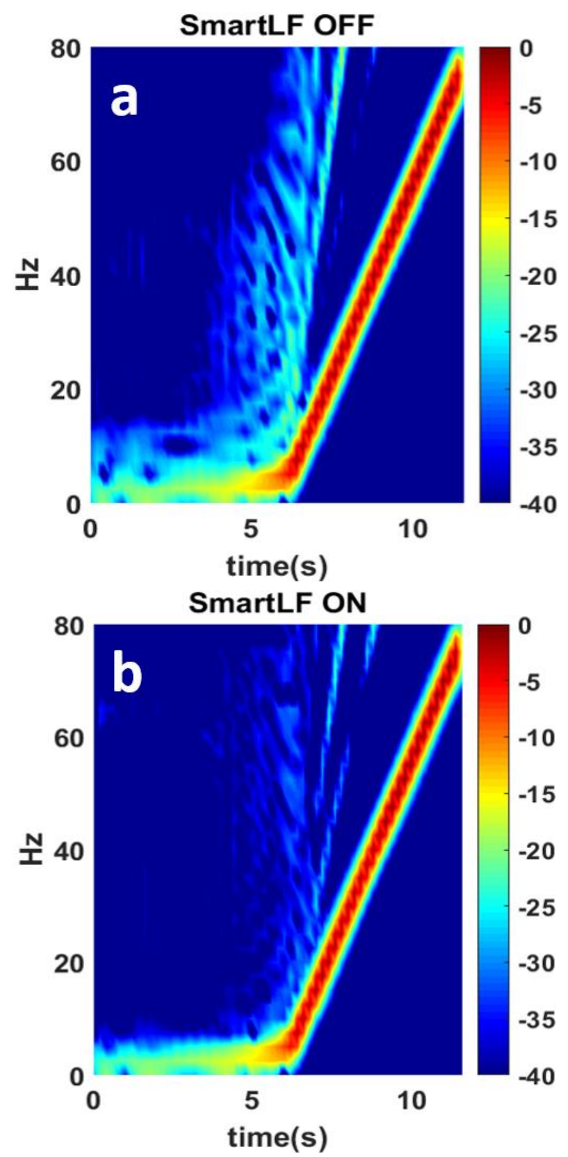

Figure 6: Low-Dwell 2-80 Hz, 12 s, 70 %. 16,135 lbf vibrator (Nomad 15), road, Northern France. (a) SmartLF off, (b) SmartLF on.

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