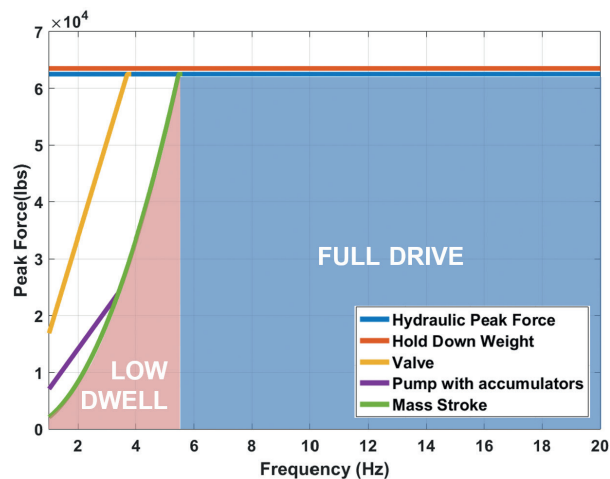


# Low-frequency Vibroseis: current achievements and the road ahead?

Nicolas Tellier<sup>1\*</sup> and Gilles Ollivrin<sup>1</sup> discuss the achievements in land seismic equipment and methods, and speculate on the future of low-frequency Vibroseis.

## Introduction

Extending the seismic signal frequency towards low frequencies has become almost standard on seismic projects, owing to the benefits it provides in terms of vertical resolution, signal penetration, inversion workflow results or ease of interpretation. Vibroseis is preferred to explosives not only for its productivity, but also for the control it allows over frequencies generated. While Vibroseis equipment has been improved in recent years, discrepancies are observed in the equipment and methods used, in particular in the design of low-frequency sweeps. A desire for lower frequencies seems also to guide the development of some vibrators, at the expense of technical complexity, higher cost and reduced performance at higher frequencies. However, if the need for broader frequencies is not questioned, the right level of low-frequency energy necessary for imaging and interpretation purposes is still not clearly defined by the industry, at the risk that the current focus for more powerful lower frequencies could be a temporary trend. This paper discusses achievements in equipment and methods, and speculates on the future of low-frequency Vibroseis.



**Figure 1** Low-frequency physical limitations of a 62,000 lbf vibrator, with associated full-drive and low-dwell areas. The full-drive area is displayed for 100% drive. However, in production the drive is in fact always lower and the full-drive area extends farther towards the low frequencies (this point will be further discussed in the next section). Note that the pump with accumulators limitation is arbitrarily displayed beneath the mass stroke limitation, which is the case for most production sweeps.

## Current approaches for generating low frequencies

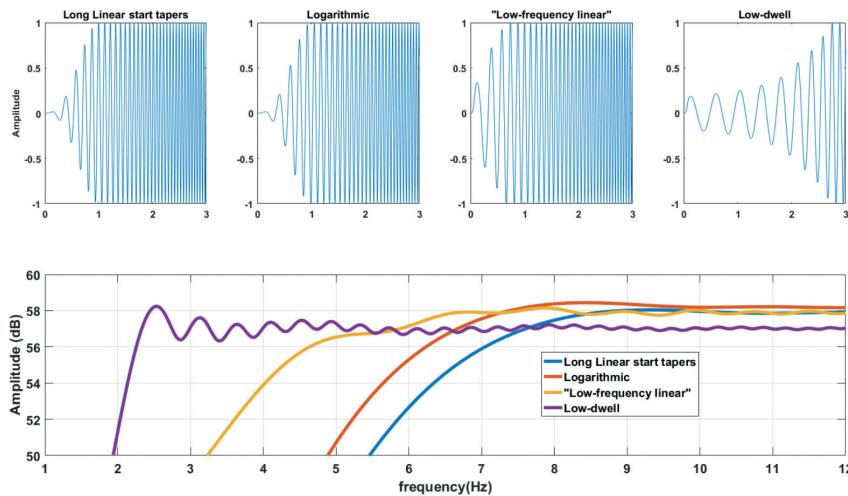
The current way to generate low frequencies with vibrators extends the signal bandwidth below vibrator ‘full-drive start frequency’ capabilities, this being the minimum frequency at which the vibrator can theoretically generate a sweep with 100% drive (e.g., a 62,000 lbf peak force vibrator generating a 62,000 lbf signal). Below this frequency, mechanical/hydraulic limitations in the vibrator design (Figure 1) require the output to be decreased (further considerations about the low-frequency capabilities of seismic vibrators will be discussed in the next section). In this regard, the traditional method is based on achieving a flat energy spectrum for the seismic signal emitted over its full bandwidth, with the use of low-dwell sweeps such as Emphaseis sweeps (Sallas, 2010) or MD-Sweep (Bagaini, 2008). With these sweeps, vibrator drive is decreased to match vibrator mechanical/hydraulic limitations; the lesser output being compensated by a slower sweep rate.

Though low-dwell sweeps are largely accepted by the industry being very often used in the most advanced commercial seismic projects, since the advent of low-frequency Vibroseis alternative ways to design low-frequency sweeps have emerged, likely owing to the difficulties met by some geophysical contractors to design and generate low-dwell sweeps. Though ‘low-frequency compliant’ on the paper, these alternative methods are nonetheless not as efficient as low-dwell sweeps (Figure 2, purple):

- Long linear start tapers. Linear tapers (e.g., sinusoidal or Blackman) are commonly used at the beginning and end of sweeps to mitigate the Gibbs effect (strong amplitude oscillation) observed at sweep edges. Their use is now sometimes extended to address requirements for low frequencies (e.g., a 7-80 Hz sweep with 250 ms taper ‘broadbanded’ in a 2-80 Hz sweep with 1000 ms start taper, Figure 2, blue). The low-frequency energy output is then determined by the parameters of the tapers selected, but not by end-user expectancy.
- ‘Low-frequency linear’ sweeps, up to the vibrator limitations (Wei, 2016). Such sweeps are similar to the previous method, though optimized in terms of energy output with regard to vibrator capability. They also do not offer any control over the low-frequency amplitude spectrum, which is determined by vibrator capability, rather than end-user expectancy (Figure 2, yellow).

<sup>1</sup> Sercel

\* Corresponding author, E-mail: nicolas.tellier@sercel.com



**Figure 2** Sweep envelopes at low frequencies (top) and low-frequency amplitude spectrum (bottom) of a low-dwell sweep with various alternative low-frequency sweeps (example with a 2-80 Hz, 12 s, 80%, Nomad 65 Neo). Full signal amplitude is reached at 2.5 Hz for the low-dwell sweep, but only at 5 Hz for the 'Linear Low Frequency', 7.2 Hz for the logarithmic sweep (-0.2 dB/oct) and 8.4 Hz for the sweep using a long 1 s linear taper.

- Logarithmic sweeps (Figure 2, red) redistribute the energy of conventional linear sweeps towards the poorly absorbed low frequencies, at the detriment of higher frequencies. Such sweeps were used mainly in the late 1980s with a focus on the high-frequency output, but were soon abandoned after a strong but short trend due to their poor efficiency. There has recently been some recurrence of their use on several projects, with a focus on the low-frequency end. However, these sweeps offer mainly a redistribution of energy toward low frequencies, with a limited bandwidth extension.

Compared with the low-dwell sweep, the three alternative methods presented above appear as attempts to extend conventional sweeps (starting around 6-7 Hz) towards lower frequencies, but do not offer any control over the level of energy generated and subsequent energy spectrum, while low-frequency signal content is paramount for processing and seismic imaging.

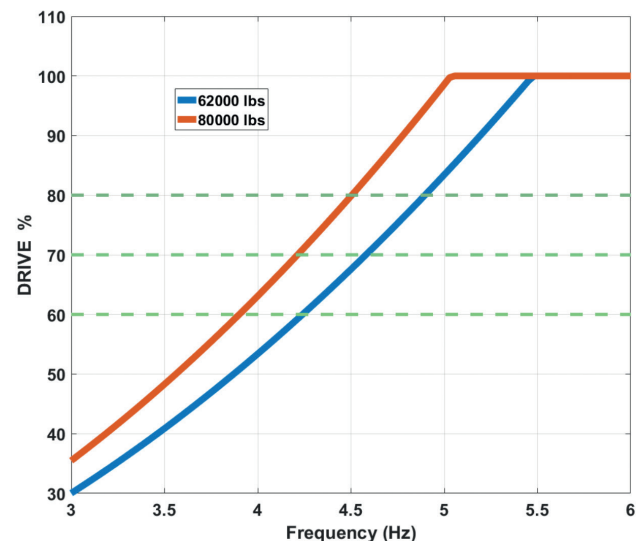
*Is current vibrator performance sufficient for today's low frequency requirements?*

Seismic vibrators had not been optimized for the generation of low frequencies until the advent of the industry concern for broadband in the early 2010s. To address this new requirement, manufacturers proposed new vibrators (Caradec, 2008) or modified the design of existing ones (Tellier, 2015a) to decrease their full-drive start frequency, from around 7 Hz to 5.5 Hz, and subsequently reduce the duration of low-dwell tapers and improve the quality of LF signal.

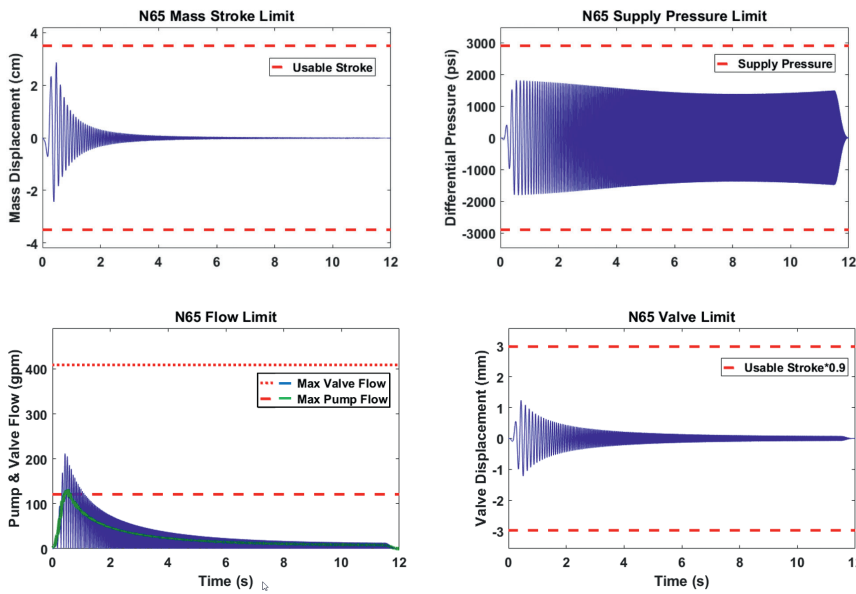
A new generation of vibrators has entered the market with even lower full-drive start frequencies. Some operators have been unusually quick to specify these vibrators' particular low-frequency full-drive capabilities in their tenders. A decision that effectively makes their use compulsory but is made with little consideration of the specifics of broadband Vibroseis:

1. As stated earlier, vibrator 'full-drive start frequency' describes the minimum frequency where the vibrator can theoretically generate a sweep with a 100% drive level. However, production sweeps are never designed at maximum vibrator capability, but with drive levels that rarely exceed 80% of full drive. The 'useable' full-drive start frequency is consequently significantly reduced (Figure 3).

2. Extended low-frequency contents are sometimes required in tenders through extended sweep bandwidths, together with linear (non low-dwell) sweeps and vibrators offering a full-drive capability from the very low start frequency of the sweep. However, this does not account for drive level (as stated in the previous point), sweep length, sweep rate and length of linear tapers used, that all have an influence on the capability of the vibrator. Figure 4 illustrates a real-world (but increasingly common) example, where tender documents require a 62,000 lbf vibrator with a full-drive capability from 3 Hz, and a linear sweep 3-90 Hz, 12s, 70% with linear 500 ms taper. However, these sweep parameters are fully compliant with a vibrator not optimized for low frequencies such as the standard Nomad 65.
3. Extending significantly the performance of seismic vibrators towards the low frequencies is performed by means of heavier reaction masses and considerably longer reaction mass strokes in conjunction with heavy, complex and expensive hydraulic systems to enable control of the very low frequencies



**Figure 3** The 5.4 Hz full-drive start frequency of a 62,000 lbf vibrator (Nomad 65 Neo, blue) is reduced to 4.9 Hz at 80%, 4.6 Hz at 70% and 4.25 Hz at 60%. With an 80,000 lbf vibrator (Nomad 90, red), the 5 Hz full-drive start frequency is scaled down to 4.5 Hz at 80% and 4.2 Hz at 70%. For comparison, at 60% (the equivalent of the output of a 60,000 lbf vibrator at 80%), the full-drive start frequency of this vibrator is in fact 3.9 Hz.



**Figure 4** Influence of sweep length, sweep rate and length of linear tapers when using linear (non low-dwell) sweeps. A linear sweep 3-90 Hz, 12s, 70% with linear 500 s taper is fully compliant with a vibrator not optimized for low frequencies (results verified using CheckSweep simulation software).

generated. If such a design is well suited to the generation of low frequencies, it is to the detriment of the vibrator capability to efficiently generate higher frequencies in the seismic bandwidth of interest, as accurate control of heavy masses then becomes speculative. Additional issues relating to oil compressibility and the large oil volumes in the actuator that result from long mass strokes tuned for low-frequency performances must also be overcome. Note that recent solutions have focused on the mass stroke limitation in particular, but other physical limitations (in particular, the servovalve capability) remain unaddressed. Table 1 displays an overview of the Vibroseis equipment limitations at low frequencies.

- It is worth noting that when compared to heavy vibrators specifically dedicated to low frequencies; existing super-heavy vibrators in fact already have excellent low-frequency performance (Caradec, 2008 and Figure 3). A balanced hydraulic design and dedicated features to ensure vibrator high-frequency performance, e.g., ultra-stiff baseplate, or

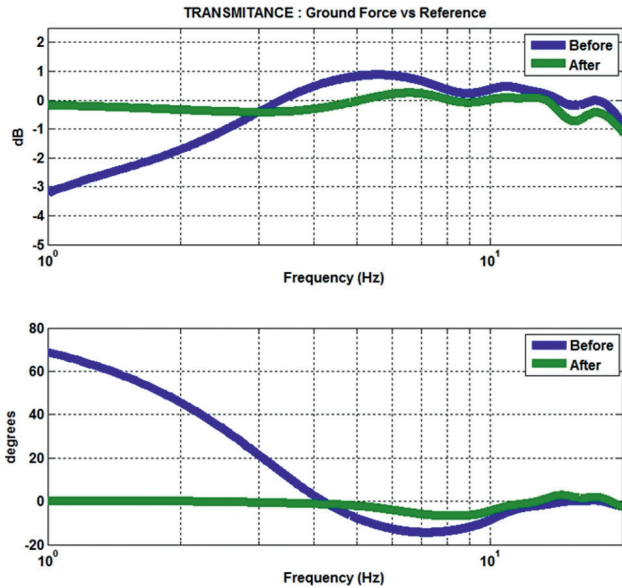
90,000 lbf hydraulic peak force heavier to the 80,000 lb hold-down weight (Tellier, 2015b) offer the industry a real broadband solution, without compromises.

*Is the performance of current vibrator control electronics sufficient for today's low frequencies requirements?*

Vibrator control electronics play a key role in Vibroseis acquisition, by controlling the overall vibration. Although considered a black box by many, their function and the subtleties of their performance has been explained in detail (Boucard, 2010). Although vibrator electronics were initially optimized for the range of frequencies most commonly used in the past (generally 8-80 Hz), manufacturers have made significant efforts over the last ten years to support the expectancies for broader frequency contents. In particular, fundamental, phase control, distortion and QC have been steadily improved to provide high-fidelity low-frequency seismic signals suitable for data inversion and interpretation:

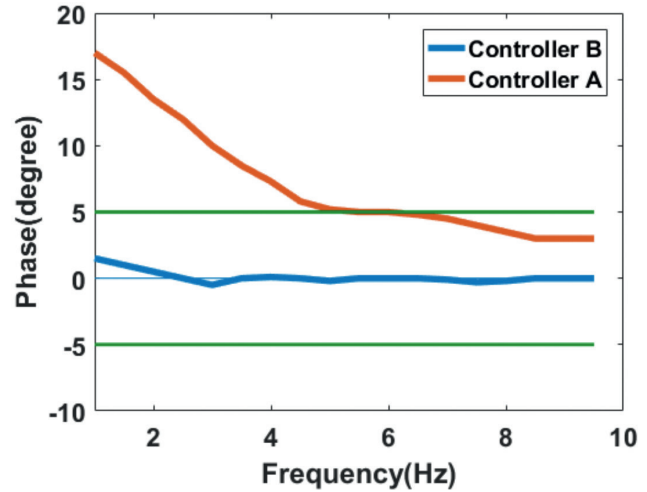
		LIMITATIONS	SOLUTIONS	SOLUTION LIMITATION / DRAWBACK
<b>LOW FREQUENCIES</b>	Full drive start frequency	Mass weight	Heavier mass	Cost / High-frequency performance
		Mass stroke	Longer mass stroke	Complex hydraulic design and maintenance High-frequency performance
		Pump and valve flow	Larger pumps / servovalves Higher pressures Proper size of accumulators	Cost and dimensions Cost and dimensions Accumulators dimensions
	Sweep quality	Vibrator non-linearity & associated distortion	Inverse distortion pilot (CleanSweep) SmartLF HDR Improved vibrator model Reduced overlap servovalve	None None Stronger 2nd harmonic Servo-control robustness Control / Compatibility with current valve design
		Pressure stability	In-built mass accumulators close to servovalve	Cost
		Valve main stage displacement	Long stroke servovalve	Valve availability and cost
		Vibrator isolation	Low-frequency isolation airbags	Contractor interest for frequencies below $\approx 1.5$ Hz
	Nearby vibrator noise	Engine and pump noise isolation	Cost / cooling issues	

**Table 1** Seismic vibrator low-frequency physical limitations, solutions, drawbacks and new limitations induced by these solutions.



**Figure 5** Amplitude and phase correction for a 1-20 Hz window: the green curve after controller correction indicates a great improvement on sweep control in low frequencies compared to the blue curve – Field tests with Nomad 65 vibrators controlled by VE464.

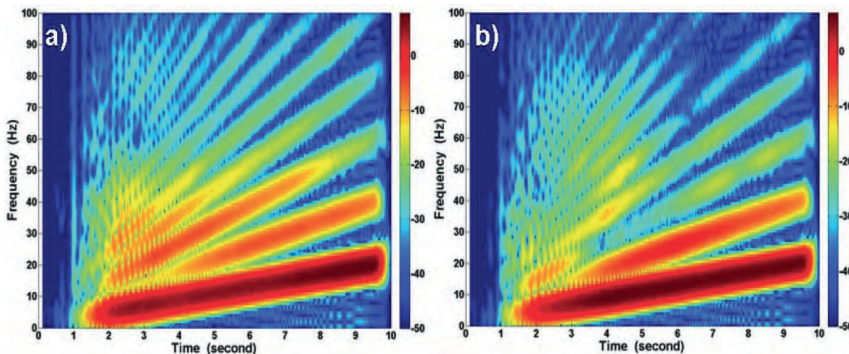
1. **Fundamental and phase shift control:** small differences in low-frequency fundamental amplitude, although not significant, were corrected in recent vibrator electronics. The more significant differences in low-frequency phase shift have been considerably reduced on controllers since 2013 (Tellier, 2014 and Figure 5). However, the low-frequency phase performance differs from one vibrator electronic model to the other, even when optimized for low-frequency control. An efficient phase control must indeed take numerous factors into account (e.g., reaction mass centred with regard to the shaker, supply pressure stability, servovalve non-linearity, vibrator physical limitations that must not be exceeded) and requires a fast and accurate servo-control to be able to keep this phase shift close to null during the entire sweep. Figure 6 displays a low-frequency phase control comparison between two controllers on sweeps starting from 1 Hz. Controller A is VibPro HD and Controller B is VE464. In contrast to the results presented by Wei (Wei, 2018), controller B is used with proper settings and a recent version (2013+).
2. **Low-frequency distortion** has its source mainly in vibrator non-linearities at low frequencies (square root relation between the oil flow and hydraulic pressure) and the servo



**Figure 6** Phase spectra produced by 62,000 lbf commercial vibrators with Controller A (linear 1-15 Hz 10 s) and Controller B (low-dwell 1-80 Hz 12 s).

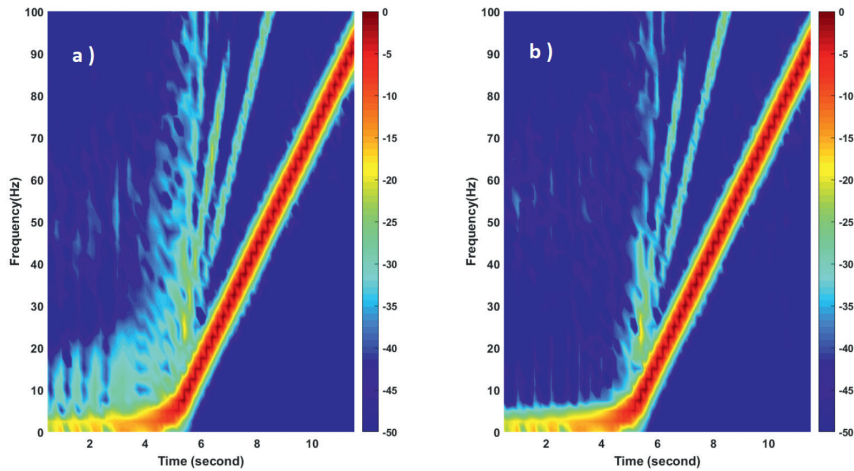
valve overlap in low frequencies (brief and sharp drop in hydraulic pressures when the servo valve passes its neutral position). This inherent distortion has been significantly reduced in recent years by different techniques. The main solutions available to date are mainly the following:

- *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, however, effective only with VE464 electronics, owing to the requirement for a fast servo-control able to accurately follow a more complex anti-distortion pilot. CleanSweep technique provides excellent distortion performance at low frequencies, as it addresses all ranks of harmonic noise.
- *VibPro HDR* technology is based on non-linear compensation of the servovalve non-linearity. All harmonics are reduced, except the second, which is strengthened. Figure 7 compares harmonic contamination with and without HDR technology.
- The recent *SmartLF* solution is embedded in the VE464 controller and optimizes the hydraulic valve modelling and management in order to characterize the low-frequency distortion and avoid its generation. This improved servo-control uses the production pilot signal without modification, and does not require extra mechanical components. SmartLF modelling and harmonic prediction efficiently addresses the majority of the low-frequency related distortion (Figure 8).



**Figure 7** 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’s brochure.





**Figure 8** Comparison of the ground force of a low-dwell, 1.5-95 Hz 12 s 80% sweep with Nomad 65 Neo. (a) SmartLF off and (b) SmartLF on. From VE464 user manual.

3. Low-frequency quality control, specifically designed to address low-dwell sweep, offers the possibility to check QC in real time for all frequencies (Tellier, 2014).

Table 1 summarizes the main low-frequency limitations of Vibroseis equipment, how they are addressed and the limitation of the new solutions. Mougénot (2018) also provides a complete review of the performance of seismic equipment for broadband acquisition.

#### *Are we too strong in low frequencies?*

If the benefits of lower frequencies in seismic datasets is fully recognized and now required on most commercial projects, there has been little discussion with regard to the level of energy really necessary for these newly recorded frequencies. Low frequencies are indeed poorly absorbed by the subsurface, and their long wavelength is largely oversampled spatially. Thus, it can be assumed that the level of energy required at low frequencies is less than that required for higher frequencies. However, the current approach for low frequency generation is inherited from:

- The existing hydraulic vibrator technology (with an effort to extend their performance towards low frequencies).
- The conventional sweep design, targeted towards a flat spectrum over the full bandwidth by means of a low-dwell taper (the alternative sweeps described in the first section are not considered, as they do not offer any control over the energy spectrum).

This approach implies:

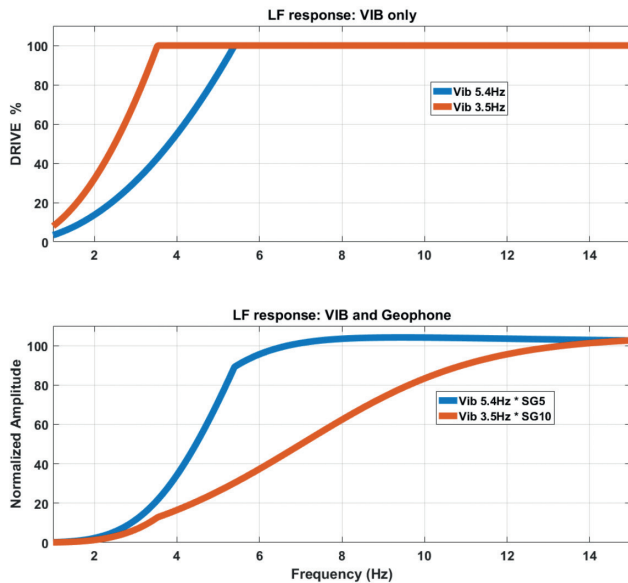
- Extra cost: expense associated with the design and maintenance of bulkier and more complex hydraulics of vibrators heavily optimized for the low frequencies; or with the low-dwell tapers that are potentially time consuming (though mitigated to some degree via simultaneous source acquisition strategies);
- And/or compromises: vibrators configured for low frequency compromising the high-frequency performance; or time spent on the low-dwell taper being made to the detriment of energy level at higher frequencies.

Hence the question: are we focusing too much on low frequencies? Can we rethink our shooting strategy, in order to have the proper level of low frequency (in terms of bandwidth and energy) that will address the geophysical problems we have to

resolve, but also provide the optimal ROI for the associated equipment and operations? Given that the answer to this question is essentially in the hands of the oil and gas companies, two likely alternatives exist:

- Review the spatial pattern of seismic signal generation with methods such as Dispersed Source Array (Caporal and Blacquièrre, 2015), where specialized sources (Reust, 2015) emit narrow-band sweeps on grids that become increasingly dense as the frequencies increase, provided contractors confirm the soundness of such an approach (more source type to manage) in terms of operational complexity and cost efficiency.
- A sweep designed with a ramp-up of energy as the frequency increases. Provided the low-frequency signal level is set to enable its propagation over long offsets while remaining above noise, shorter sweeps can be designed, without the need for ever-improved vibrators.

A last point to be considered is the respective contribution of sources and sensors in adequate recording of low frequencies. While optimized sources provide a few dB improvements in signal generated, current high-end geophones provide around 12 dB more on the entire bandwidth owing to their higher sensitivity (e.g., 80 V/m/s instead of 22 V/m/s), and 12 dB more due to their lower natural frequency (5 Hz instead of 10 Hz). Providing an accurate evaluation of the contribution of sources and sensors is not an easy task, as it depends on numerous parameters (vibrator output and low-frequency performance, sensor and geometry used, low-frequency ambient noise, low-frequency noise generated by idle vibrators on the spread) and is always the result of a cost compromise for commercial projects. A very simplified evaluation is proposed in Figure 9, with the outputs of two ‘virtual’ vibrators having theoretical full drive start-frequency at 5.4 Hz and 3.5 Hz multiplied respectively by the responses of 5 Hz and 10 Hz geophones. In addition, the latest MEMS accelerometers achieve unprecedented performance at very low frequencies, which make them fully compliant for very low-frequency recording, without phase distortion (Fougerat, 2018). In time, the industry will answer these questions through accurate evaluation and comparison of sources and receivers, in field conditions through to final imaging, while taking into account the cost issues in order to better provide manufacturers with clear guidelines.



**Figure 9** Simplified model of the response of two vibrators with regard to two geophones.

### Conclusion

If the requirement for lower frequency content in datasets is not questioned, the optimum level of energy that has to be generated and recorded remains unclear. The current focus on ever stronger low frequencies may result in disproportionate solutions in terms of acquisition and equipment, that may result in it being only a short term trend, as was the case with log sweeps in the late 1980s. It is worth noting that successful low-frequency imaging has been reported on major projects using standard vibrators (not optimized for low frequencies) and low-dwell sweeps, with no compromises on productivity and cost (e.g. in Oman with Inova PLS 362 (Mahrooqi, 2012) and more recently in Egypt with standard Nomad 65 (Yanchak, 2018)).

Currently, alternative sweep design solutions, though strictly speaking answering tender requirements in terms of bandwidth, do not offer any control over the low-frequency energy spectrum and make the recovery of these frequencies speculative.

Current Vibroseis equipment has been improved to better address low frequencies, while preserving the overall equipment cost and broadband performance, thus enabling the acquisition of any survey with equipment from the current industry standard inventory. If the recent efforts in respect of vibrator electronics delivers as promised (in particular for the distortion reduction), pushing the low-frequency performance of existing vibrator actuator technology further results only in complex and overpriced solutions, while compromising the quality of higher frequencies. Existing 80,000 lb super-heavy vibrators optimized for both low and high frequencies already display excellent performance over the entire bandwidth of interest to the seismic industry. The contribution of sensors, such as low-frequency high sensitivity geophones, or MEMS accelerometers that now provide unprecedented performance at low frequencies together with excellent phase stability, will be evaluated in more detail as well.

Clarifying industry trends towards stronger lower frequencies and the expectancy in terms of associated energy, while

confirming the relevance of methods such as Dispersed Source Array (with associated narrow-band sources) and sweeps designed to ramp-up as the frequency increases (at least at the low-frequency end), would definitely help to make Vibroseis equipment and associated seismic operations more optimally suited to the industry's needs, both in terms of performance and cost effectiveness.

### Acknowledgments

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### References

Bagaini, C. [2008]. Low-frequency Vibroseis data with maximum displacement sweeps. *The Leading Edge*, 582-591.

Boucard, D. and Ollivrin, G. [2010]. Developments in vibrator control. *Geophysical Prospecting*, **58**, 33-40.

Caporal, M. and Blacquièrre, G. [2015]. Broadband seismic by means of dispersed source arrays. *EAGE Workshop on Broadband Seismic*, Extended Abstracts.

Caradec, G. and Buttin, P. [2008]. Development of a super-heavy vibrator. *EAGE Vibroseis workshop*, Extended Abstracts.

Castor, K., Bianchi, T., Winter, O. and Klein, T. [2014]. Noise Reduction in Vibroseis source. *84<sup>th</sup> SEG annual meeting*, Expanded Abstracts.

Fougerat, A., Guérineau, L. and Tellier, N. [2018]. High-quality signal recording down to 0.001 Hz with standard MEMS accelerometers. *88<sup>th</sup> SEG annual meeting*, Expanded Abstracts.

Mahrooqi, S., Rawahi, S., Yarubi, S., Abri, S., Yahyai, A., Jahdhami, M., Hunt, K. and Shorter, J. [2012]. Land seismic low frequencies: acquisition, processing and full wave inversion of 1.5 - 86 Hz. *82<sup>nd</sup> SEG annual meeting*, Expanded Abstracts.

Mougénot D. [2018]. Marine, seabed, and land seismic equipment for broadband acquisition: a review. *Geophysical Prospecting*, **66**, 922-933.

Reust, D., Johnston, O., Giles, J. and Ballinger, S. [2015]. Very low frequency seismic source. *85<sup>th</sup> SEG annual meeting*, Expanded Abstracts.

Sallas, J. J. [2010]. How do hydraulic vibrators work? A look inside the black box. *Geophysical Prospecting*, **58**, 3-18.

Tellier, N., Ollivrin, G. and Boucard, D. [2014]. Optimizing the generation and QC of low-dwell sweeps. *76<sup>th</sup> EAGE Conference and Exhibition*, Extended Abstracts.

Tellier, N., Ollivrin, G. and Boucard, D. [2015a]. Vibroseis equipment for efficient low-frequency generation and high-productivity operations. *First Break* **33**, 73-79.

Tellier, N., Ollivrin, G. and Caradec, G. [2015ab]. Higher vibrator hydraulic force for improved high frequency generation. *77<sup>th</sup> EAGE Conference and Exhibition*, Extended Abstracts.

Wei, Z. [2016]. Linear low frequency sweep vs customized low frequency sweep. *86<sup>th</sup> SEG annual meeting*, Expanded Abstracts.

Wei, Z. [2018]. Vibroseis controllers – are your low frequency sweeps in phase. *88<sup>th</sup> SEG annual meeting*, Expanded Abstracts.

Yanchak, D., Monk, D. and Versfelt, J. [2018]. Egypt West Kalabsha 3D broadband ultra high density seismic survey. *88<sup>th</sup> SEG annual meeting*, Expanded Abstracts.