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Vibrator Evolutions for Broadband Performance: Accomplishments and Remaining Issues

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SUMMARY

Extending the frequencies available for seismic imaging has been a key priority for the industry in recent years, so extra octaves of signal have to be generated. However, the design of vibrators implies limitations that differ with frequency. After a review of the main vibrator limitations at low and high frequencies, the proposed abstract presents the main improvements achieved up until now, and the limitations that are still pending.

Introduction

Vibrators have long been optimized for the 8-80 Hz bandwidth requested by the industry. This expectation evolved in recent years to improve seismic imaging quality: broadening the dataset frequency content enhances the vertical resolution and improves velocity model and inversion efficiency. A more accurate imaging can be produced and thin layers or faults detected. Vibrators are part of this new expectation: their design evolves to overcome the physical limitations that compromise the efficient generation of these new frequencies.

Vibrator limitations

Vibrator technological design implies physical limitations at both low and high frequencies. At low frequencies, the vibrator behavior is hardly ground dependent: it is well known and can be accurately modeled. Manufacturer's technological choices will mainly have an influence on the vibrator full-drive start frequency, given by the formula:

$$Fmin = \frac{1}{2\pi} \times \sqrt{\frac{Min(HPF, HDW)}{Mmass \times \frac{Usable\ Stroke}{2}}}$$

Below this frequency, Sallas (2010) showed that vibrators are affected by several limitations:

- Mass stroke, i.e., the mass maximum displacement.
- Pump flow, i.e., the pump ability to answer the strong flow oscillations imposed by low frequencies.
- Valve flow, equivalent of the above for the valve.

When using mass accumulators of proper size, the mass stroke becomes the key limiting factor.

Modern vibrators can operate below their full-drive start frequency, but with a reduced drive. Custom sweeps are then required, designed with a low-frequency ramp-up, for which the drive level at any frequency remains within vibrator capability (Bagaini 2007, Sallas 2010). However, preserving a flat spectrum on this ramp-up implies that for a given frequency, the sweep duration has to be increased by the square of the drive reduction, which may impact crew productivity. The low-frequency vibrator limitation is then more a productivity issue than a capability one (Tellier 2014).

However, other factors affect the sweep quality at low frequencies. Pump response time is limited but can be compensated using accumulators of proper size. The servovalve dwells longer on its neutral position (valve overlap): it produces a succinct hydraulic pressure drop resulting in a brief amplitude trough on the recorded wavelet. Valve main stage maximum displacement is usually reached at frequencies around 5-7 Hz. Lastly, the vibrator system is non-linear, particularly at low frequencies where higher distortion is generated.

The issue is different in high frequencies, where the ground influence is paramount. Higher frequencies can be more effectively generated on a hard ground than on a soft ground. In addition, vibrator design implies various limitations. Baseplate coupling and stiffness are a recognized issue (Ley, 2006). The increasing with frequency mass to baseplate acceleration phase shift makes hydraulic pressure reach its maximum, resulting in a ground force drop above a certain frequency which depends on the ground type. Servovalve response also stops being linear above around 100 Hz, making the output flow drop.

Improvements

Numerous limitations mentioned above have been successfully addressed in recent years. At low frequencies, a heavier reaction mass, a larger mass stroke, and a higher differential pressure enable lowering the vibrator full-drive start frequency, and thus increasing the productivity for very low-frequency acquisitions. Sweep quality is ensured thanks to improved servovalves that properly monitor the system's higher hydraulic pressure. In addition, improved hydraulic systems and accumulators installed as close as possible to the servovalve reduce the important pressure transients associated with the low-frequency large amplitude mass oscillations. The distortion associated with vibrator non-linearity at low frequencies can be effectively addressed by injecting the opposite of the harmonic signal in the source input (Castor, 2014). Such a solution addresses servovalve overlap. Valves with reduced overlap can be used also, but until now they have induced other problems.

At high frequencies, baseplates are more likely to flex. The baseplate accelerometer will record this flexure and interpret it as a contribution to the ground force. A stiffer baseplate smoothens this artifact: an extra bandwidth can be effectively generated, and the vibrator QC will show better correlation with the true down-going signal. The issue is similar for baseplate accelerometer location: even with stiffer baseplates, accelerometers located at different positions will output different signals. A proper combination of accelerometers can provide a QC much closer to the reality, and thus improve the generated signal fidelity. A hydraulic peak force exceeding the vibrator hold-down weight provides additional hydraulic margin to compensate for the mass to baseplate increasing phase shift and enables the efficient generation of an extra bandwidth (Tellier 2015). Lastly, as for low-frequency, stable and well-controlled hydraulic pressures prevent reaching the maximum available pressure.

	LIMITATIONS		SOLUTIONS	SOLUTION LIMITATION / DRAWBACK
LOW FREQUENCIES	Full drive start frequency	Mass weight	Heavier mass	Cost / Vibrator weight & dimensions
		Mass stroke	Longer mass stroke	Increased pressure: hydraulic component capacity
		Pump and valve flow	Larger pumps / servovalves Proper size of accumulators	Cost and dimensions / Higher pressures Accumulators dimensions
	Sweep quality	Vibrator non-linearity	Inverse distortion pilot Improved vibrator model	None Servo-control robustness
		Pressure stability	Accumulators close to servovalve	Reaction mass design limitation
		Valve main stage displacement	Long stroke servovalve	Valve availability and cost
		Valve overlap	Reduced overlap servovalve	Control / Compatibility with current valve design
		Vibrator isolation	Low-frequency isolation airbags	Contractor interest for very low-frequency
HIGH FREQUENCIES	GROUND	Ground random behaviour Baseplate coupling	High dwell sweeps	Repeatability
	Sweep quality	Baseplate stiffness	Stiffer baseplates	Baseplate weight and cost
		Mass to baseplate phase shift	HPF > HDW	Hydraulic component capacity
		Servovalve bandwidth	Improved servovalve Alternative technologies	Technologies not ready
		Pressure stability	Accumulators close to servovalve	Reaction mass design limitation
	QC fidelity	QC consistency with true emitted signal	Multi accelerometers Filtered mode Stiffer baseplates	None None Baseplate weight and cost

Figure 1 *Seismic vibrator physical limitations, solutions, and drawbacks and new limitations induced by these solutions, at low and high frequencies.*

Remaining issues

Vibrator low-frequency performance has been well-addressed thanks to the numerous improvements listed above. Two main remaining issues can be identified:

- Further reducing the full-drive start frequency, thanks to even heavier reaction masses and even larger mass strokes. However, this implies very important hydraulic flows and a

complete redesign of the hydraulic system. The main interest of such a solution is an enhanced productivity for very low frequency acquisition.
- Exploring very low frequencies, below 1 Hz. This implies other limitations, such as isolation of the truck with respect to the shaker, which is currently performed with isolation airbags that are theoretically efficient down to 1.5 Hz. However, do operators have an interest in recording such low frequencies? Other limitations shall indeed be taken into account at such low frequencies, such as extensive sweep duration, sensor natural frequency, and ability to preserve the very low amplitude signal during processing.

At high frequencies, the main limiting factor remains the ground, and the baseplate coupling that can be easily disturbed by an uneven terrain relief. Improvements can nonetheless be expected on servovalve bandwidth specification and ground models. However, complex models usually show little compatibility with the production environment. Manufacturers currently have the knowhow to produce the lightest and stiffest possible baseplates, but are all end-users ready to accept the extra cost induced by the required materials (e.g., titanium, composite) and manufacturing technologies?

Several solutions already exist to improve the generation of high frequencies but are still rarely employed on the field. The use of a QC-filtered mode, based on estimated states instead of raw measurements and derived from a Kalman filter, produces a ground force showing better correlation with the true emitted signal. High-dwell sweeps are shaped with a reduced drive when frequencies increase. When ground influence becomes paramount, they avoid reaching vibrator limitations and reduce distortion. As for their low-dwell equivalent, their use implies either a smoother amplitude or a longer sweep, which are acceptable compromises for an optimally controlled sweep.

Conclusion

In the past, numerous limitations prevented the optimum generation of broadband sweeps. Most of them have been, or are being addressed, as long as they remain compatible with contractors' cost constraints. At low frequency, the issue is firstly a question of productivity, as for high frequencies when high-dwell sweeps are used. However, broadening the sweep bandwidth implies either increasing the sweep length or spending less time on the 8-80 Hz frequency range, and thus recovering a lesser amplitude signal. This has to be closely considered, even if high productivity techniques enable more flexibility on sweep length.

References

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