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Marine vibrator source: Modular projector system

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Summary

There is a desire by the marine geophysical industry for a seismic source with a low environmental footprint. Received sound pressure level (SPL) and sound exposure level (SEL) can restrict how seismic surveys can be conducted in sensitive areas.

To address this desire, we have developed a broadband non-impulsive source based on the concept of modular transducer elements. The source has a controlled output that can emit arbitrary signals, enables flexible source geometries, and can produce ultra-low frequency content that facilitates robust full waveform inversion.

Sea trials and testing indicate that the developed source will meet the challenging output demands and exhibit the necessary robustness to be a viable seismic source for the future. Large scale testing is planned in 2019.

Introduction

There are several ongoing initiatives of seismic source development within the marine seismic industry. Improved source solutions have been presented using both traditional air guns (Gerez et al., 2015) and marine vibrators (Feltham et al., 2017). Lowering the SPL and SEL are relevant for seismic surveys in environmentally sensitive areas, since these form thresholds for how surveys may operate at various distances from observed marine mammals, marine parks, commercial fisheries, etc. (Duncan et al., 2017).

In comparison to the traditional marine air guns which can only generate an impulsive signals, marine vibrators are non-impulsive and therefore offer additional signal control options. Some of the possible advantages of marine vibrators include (1) operation at lower SPL value for fixed required SEL, (2) controlled signal output which gives opportunities for new and flexible source geometries, (3) potential for ultra-low frequency 1-6Hz output to benefit full waveform inversion (Rietsch, 1977; Dellinger et al., 2016; Brenders et al., 2018). In order to address these benefits, we are developing a new non-impulsive marine seismic source as an alternative to traditional impulsive marine seismic sources.

The broadband system

Like most marine vibrators, our source generates an acoustic wavefield by actuating a vibrator surface to displace the surrounding water. Our basic vibrator element consists of two parallel plates actuated toward and away from each other. Arranged in proximity to each other, a multitude of these vibrator elements forms a modular projector system (Armstrong, 2015). Because the vibrator's output pressure is proportional to the plate acceleration, the plate motion needs to increase at lower frequencies as $1/_{f^2}$ in order to keep the output at a constant level (Söllner and Orji, 2018). Hence, the lowest frequencies of the seismic spectrum are the most challenging to produce. This relationship holds for the seismic frequencies at which the vibrator is small compared to the dominant wavelength, and the radiated power depends only on the displaced volume (Kinsler et al., 2000). Consequently, in order to achieve a desired pressure output over the entire frequency band, the source was divided into Low Frequency (LF) and High Frequency (HF) modules.

Figure 1. The low frequency module.

The LF module is specially designed to drive a large radiating area at small displacement, whereas most other current solutions drive small radiating areas at large displacement (Roy et al., 2018; Tenghamn and Long 2006). This is achieved by building one folded surface covering small cylindrical connected cavities as shown in Figure 1.

The advantage of using small instead of large displacements is that the vibrating elements are exposed to lower vibration stresses which implies a longer service life and lower acoustic distortion. Additionally, the small displacements can be accommodated by a bending metal interface, rather than rolling elastomeric or sliding seal interfaces required by

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large-displacement vibrators. The LF module is built to achieve full power output down to 75m operating depth, allowing it to exploit the surface ghost's otherwise negative impact at low frequencies. The source system also contains a control system capable of transmitting arbitrary coherent signals, on-board motor drive amplifiers, active pressure compensation, and comprehensive source monitoring.

System Testing

The basic system design was developed over a number of years, maturing by 2016. Recent efforts have been focused on proving operational reliability and scaling up from single module calibrations to multi-module full band exercises. Both the LF and HF modules have undergone multiple sea trials (see Figure 2 and Figure 3) at different depths and full power.

Figure 2: High frequency module at Seneca Lake test facility

Figure 3: Low frequency module sea trial in Bedford Basin, Canada.

A single LF module is capable of covering the 1-10Hz band with similar performance both shallow and deep. The LF module has been tested at various frequencies from 1-45Hz. Figure 3a shows time plots of measured near field hydrophones from the LF module at 15m, 30m, 52m and 60m depths for 24s linear sweep from 3-6Hz. Figure 3b shows the amplitude spectra of the corresponding far-field signatures. These signatures have been computed by extrapolating the pressure and the pressure ghost to 9km vertical depth and afterwards removing the spherical spreading relative to 1m distance from the source. The shallowest output though attenuated by ghost is above 180dB.

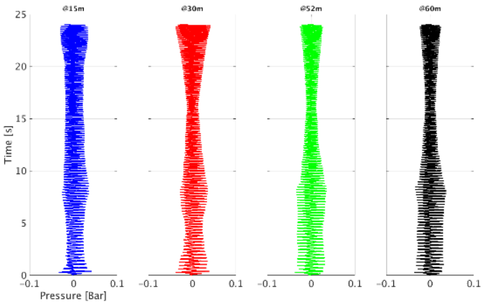

Figure 3a: Measured output from the LF module at for different depths. Input signal is 24s, 3-6Hz linear sweep

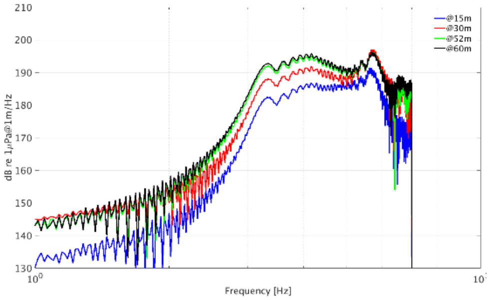

Figure 3b: Amplitude spectra of the computed far-field from 3a.

Though the LF module is optimized for deep tow and ultra-low frequencies, its frequency band and depth of operation can be changed as desired. Thus, the LF module is flexible and can be used for specialized low frequency acquisition or it can complement the HF module in situations when broadband output are required. Figure 4 show amplitude spectrum of computed far-field from nearfield measurements of the LF for 30s linear sweep from 1-45Hz (red), the 5s equivalence is shown in blue. The HF module is more compact with higher peak power, but cannot achieve as much low frequency power. In order to cover 1-100Hz the HF was swept from 35-100Hz. The computed notional source characteristics for 5s is shown in Figure 5.

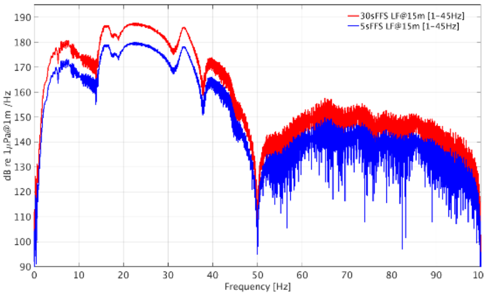

Figure 4: Amplitude spectra of the computed far-field from the LF module covering 1-45Hz.

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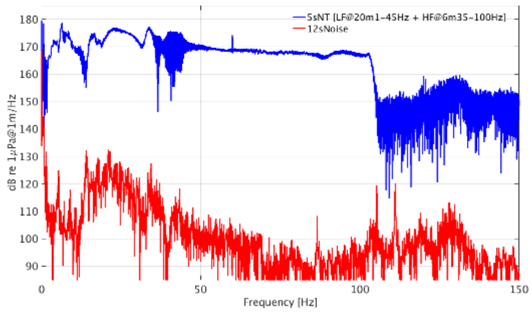

Figure 5. Amplitude spectrum of the computed notional from the measurements using LF and HF modules

The plots shown in Figures 3-5 are for one LF module and a single HF module. Since the system is modular, different configurations of the full source can be put together depending on geophysical and environmental requirements. In addition, it is an inherently low distortion system with little energy loss outside the active band as shown in Figure 5. HF module was demonstrated at the Seneca Lake test facility in December 2017. The LF module has undergone extensive in-laboratory tank testing, including a successful 1,000 hour lifetime test in spring 2017. The system has matured enough to justify a preproduction build of an additional LF module and HF modules in 2018/2019 to support planned field trials in 2019.

Source response curves are presented in Figure 6. The response of the HF module is essentially flat outside the resonant frequency of the system. Variants of the system with desired resonance frequencies are also possible (see Figure 6).

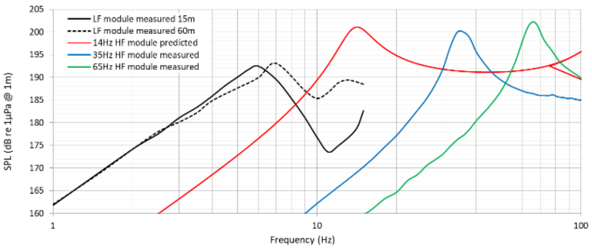

Figure 6. Source response of the modules. LF module tested at 15m (black) and 60m (black dashed) depths, and all HF modules at 15m. The HF module resonant frequency is tuned: test data for 35Hz (blue) and 65Hz (green) tunings are presented alongside predicted output for the 14Hz tuned (red) units currently in production.

Both amplitude and phase of the output from the system are controllable and repeatable, allowing arbitrary signal generation. Active distortion reduction algorithms such as iterative learning control (ILC) are used to suppress in-band and out-of-band distortion as shown in Figure 7. This is essential in reducing environmental footprint. Moreover, if a desired constant signal-to-noise ratio is desired over a given frequency band this can also be obtained by training the ILC to generate a desired signal shape. In Figure 8a the unique ability of the source to play arbitrary signals is demonstrated. Top panel of Figure 8a show 3 different shots acquired over 250s. The first 2 shots were generated at a lower power in comparison to the last shot. The signals are pseudo random sequences that are 10s long (see panels 2-4 of Figure 8a). The signal frequency band covers from 25-100Hz. Figure 8b show the scaled input current (red) and the measured pressure output. Note that the input current is in phase to the output pressure. This simplifies the process of generating arbitrary signal by the system, since the current and the output pressure are directly related (only a scaling factor needs to be determined). Thus the source can be used in a versatile manner without difficulty.

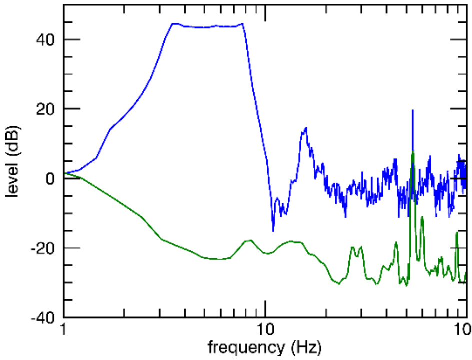

Figure 7. Application of harmonic distortion suppression using a 20s long, 3-8Hz test sweep: the amplitude spectrum of the test sweep is shown in blue and the background noise is shown in green.

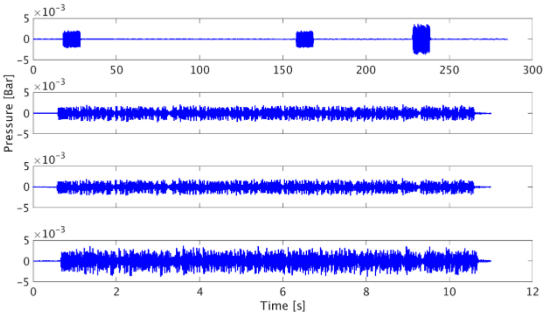

Figure 8a. Measured pseudo-random sequence generated by the HF module. The top panel shows the 3 shots with the first two shots generated at a lower power compared to the 3rd shot. Panels 2-4 show zoom of the shots from the top panel.

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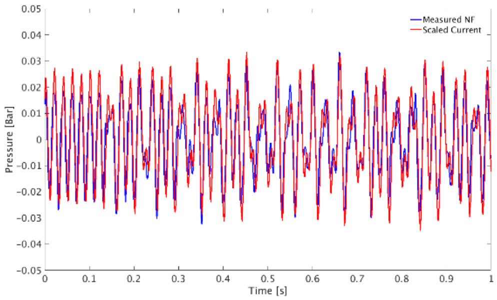

Figure 8b. A zoom of the measured pseudo-random sequence generated by the HF module (blue) and the scaled input current (red).

Discussion on implementation

The results shown in this paper have been based on one LF and one HF module. A commercial system will consists of several modules typically arranged in tow bodies. The tow-bodies can consist of one or multiple marine vibrator modules. The commercial system will then consist of several tow bodies depending on geophysical and environmental requirements. The tow-bodies can either be connected to a surface float as today's conventional marine seismic source systems, or towed directly from the body with build-in individual depth control.

Even if the new source system with its unique module elements are specialized, the system is designed to utilize as much as possible of existing operational vessel equipment. It has been key to design the overall system within existing seismic vessel back deck configuration envelop. An easy introduction of the technology without rebuilding and re-designing already existing seismic vessels has been important. To be able to meet these requirements there will be an overall size and weight limitation to the system. These limitations are directly linked to the output efficiency and tow stability at operational depth. Some of the existing equipment are buoyancy floats, source cables for connection to the tow body, feeding power and communication. Other important existing equipment is deployment and recovery installations. Lifting booms and winches are well integrated for best vessel back deck space utilization. Deployment and recovery capability is again balanced with best vessel back deck space utilization of current marine seismic source system. These are constraints to which the new marine vibrator system needs to be bound for achieving a cost efficient technology introduction.

Another element is to utilize known deployment and recovery methods. Well known procedures and methods for deployment and recovery of relative large and heavy equipment are in place. These have to function in a safe and reliable way also in rough and marginal sea conditions. The marine vibrator system described here has been designed based on all the above mentioned aspects. We are confident that a commercial system will require a minimum adjustments to the existing marine seismic vessel back deck design. The number of source modules for both the low frequency and high frequency configured into tow-bodies, and the number of bodies will fit within current marine seismic vessel back deck.

Conclusions

We have developed and tested a unique, non-impulsive marine seismic source that uses small displacements of large surfaces to reliably produce high output across the seismic band. With high amplitude and phase control, this coherent system is capable of arbitrary signal generation. The system outputs a minimum of energy outside the operating frequency band, and the modular nature of the system makes it possible to compose a tailored output taking environmental impact into account. The source has undergone over 1,000 hours of lifetime testing, and performed consistently across multiple sea trials in 2017 and 2018. The SPL of the emitted source wavefield has reached a level which meets both the expected level related to the system size and the specifications estimated from geophysical modeling. Based on these successful results, we plan to build additional source modules to support a larger scale test in 2019.

The flexibility of the modular projector system allows the source system to be optionally configured to operate as a very low frequency source only. This can be facilitated by only operating one or several low frequency modules configured in one or several tow-bodies depending on the desired output signal. Such low frequency module has been tested for a designed frequency band between 1-10 Hz at 75m sea depth. Measured data has proven this capability with competitive SPL values within the seismic industry.

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REFERENCES

Armstrong, B., 2005, Underwater sound projector system and method of producing same: U. S. Patent US8139443B2.

Brenders, A., J. Dellinger, C. Kanu, Q. Li, and S. Michell, 2018, The Wolfspar® field trial: Results from a low-frequency seismic survey designed for FWI: 88th Annual International Meeting, SEG, Expanded Abstracts, 1083–1087, https://doi.org/10.1190/segam2018-2996201.1.

Dellinger, J., A. Ross, D. Meaux, A. Brenders, G. Gesoff, J. T. Etgen, and J. Naranjo, 2016, Wolfspar®, an "FWI-friendly" ultralow-frequency marine seismic source: 86th Annual International Meeting, SEG, Expanded Abstracts, 4891–4895, https://doi.org/10.1190/segam2016-13762702.1.

Duncan, A. J., L. S. Weilgartb, R. Leaperc, M. Jasnyd, and S. Livermore, 2017, A modelling comparison between received sound levels produced by a marine Vibroseis array and those from an airgun array for some typical seismic survey scenarios: Marine Pollution Bulletin, **119**, no. 1, 277–288, https://doi.org/10.1016/j.marpolbul.2017.04.001.

Feltham, A., M. Girad, M. Jenckerson, V. Nechayuk, S. Griswold, N. Henderson, and G. Johnson, 2017, The Marine Vibrator Joint Industry Project: four years on: Exploration Geophysics, **49**, 675–687, https://doi.org/10.1071/EG17093.

Gerez, D., H. Groenaas, P. Larsen, O. Wolfstirn, and M. Padula, 2015, Controlling air-gun output to optimize seismic content while reducing unnecessary high-frequency emissions: 85th Annual International Meeting, SEG, Expanded Abstracts, 154–158, https://doi.org/10.1190/segam2015-5843413.1.

Kinsler, L. E., A. R. Frey, A. B. Coppens, and J. V. Sanders, 2000, Fundamentals of acoustics, 4th ed.: John Wiley & Sons, 560 pp.

Rietsch, E., 1977, Computerized analysis of vibroseis signal similarity: Geophysical Prospecting, **25**, 541–552, https://doi.org/10.1111/j.1365-2478.1977.tb01186.x.

Roy, D. A., R. Rekos, C. Brideau, T. Lawry, and C. Corrada, 2018, A marine vibrator to meet the Joint Industry Project specification: 88th Annual International Meeting, SEG, Expanded Abstracts, 97–101, https://doi.org/10.1190/segam2018-2997347.1.

Tenghamn, R., and A. Long, 2006, PGS shows off electrical marine vibrator to capture 'alternative' seismic source market: First Break, **24**, 33–36.