**Developing a Novel Marine Vibrator System**

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This paper was prepared for presentation during the 18th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 16-19 October 2023.

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# Abstract

This paper, and its accompanying presentation, is areport on the development and testing of the BASS marine vibrator system. Through this work we showcase marine vibrators as a viable alternative to conventional airgun-based sources both from an operational, environmental and a geophysical perspective.

# Introduction

Seismic vibrators have been used on land since the early days of seismic exploration. However, their use at sea has been more limited. According to Landrø and Amundsen, (2018) marine vibrator sources were first adapted from land vibrators in the late 1960s. See for example Brown and Fair, (1967) for one of the early patents on a marine vibrator. At this early time the development was driven by Conoco with contractors like Olympic Geophysical, Petty-Ray and later Seiscon doing much of the work.

In the late 1960s and early 1970s marine vibrators provided a good signal, but the vibrator signal length of 10–12 seconds followed by a listening period of 6–8 seconds made the method a bit ineffective compared to the alternative airgun-based method. Furthermore, vibrators systems were downtime prone. The result of this was that the seismic industry quickly switched to using airguns, which since the early 1970s, have dominated the market.

However, today there are three perceived drivers for marine vibrators. They are:

* Improved survey efficiency
* Improved seismic imaging.
* Reduced environmental impact.

This has resulted in a renewed interest in this source technology and is the background for the work presented in this abstract.

Marine seismic vibrators emit their energy spread out over time, as opposed to airguns, which emit the energy in a single, high-intensity pulse. In actual numbers the peak pressure from a vibrator array may typically be around two orders of magnitude smaller than what is emitted by an airgun array. This ‘soft' output might give the marine vibrator an environmental advantage even if the total acoustic energy emitted was the same (Southall et al., 2007; Matthews et al., 2021; Southall et al., 2019).

A second environmental advantage stems from our ability to control the energy spectrum of the source. The spectrum can be tailored to be the minimum needed to satisfy the imaging requirements (Laws et al., 2018a).

Control of the spectrum also allows marine vibrators to emit energy mainly within the seismic band [3-150] Hz, thus strongly reducing unwanted high frequency noise.

The efficiency advantage of marine vibrators stems from the ability to control the phase of the emitted signal. This feature can be used to enable novel techniques like simultaneous sources with high multiplicity and to create directional sources that allow for improved crossline interpolation. Scenarios using synthetic-data studies show increased efficiency and/or image quality compared with airguns encoded with random dithering (Halliday et al., 2018).

# Method

The BASS (Broadband Acoustic Seismic Source) vibrator system has been in development for more than a decade. The system has recently been through a series of progressively more complex trials and is now feature complete.

An operational setup will consist of multiple vibrators units. Shallow towed vibrators will typically emit high band signals in the [25-150] Hz band, while more deep towed units will emit low band energy typically in the [3-25] Hz range. This will allow us to emit acoustic energy in the full seismic band [~3-150] Hz.

It will also be possible to use the system as a low band mode, where for example only signals in the [~2-8] Hz range are emitted.

The overall number of vibrators deployed will be a function of the acoustic signal strength that is needed to image the geophysical target. See for example JafarGandomi et al., 2021.

The basic towing setup for one single high band (shallow tow) and low band (deep tow) unit is shown in Figure 1.

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*Figure 1. Drawing of the towing-setup where a vibrator is towed below a float. Top: A shallow tow high band unit. Bottom: A deep tow low band unit.*

By having two vibrator units' side-by-side we can also generate so-called dipole (gradient) sweeps. In consecutive sweeps we can alter the phase such that the units are either in phase (monopole) or 180° out of phase (dipole). The resulting source radiation patterns illustrated in Figure 2 allows for improved crossline interpolation, which translates into gains in either acquisition efficiency or imaging quality.

We have also been testing functionalities and developing software algorithms related to 4D repeatability (Elboth et al. 2022), deblending, residual sweep noise attenuation (Laws et al., 2018a), and imaging with harmonics (Wang et al., 2023). The processing algorithms have been assessed for performance using modelled synthetic data. Data from stationary field trials was also used. All these functionalities are thought relevant for a commercial system.

On the 4D side there are two quite different challenges. The first relates to how to do a vibrator repeat on a vibrator baseline. We believe the solution will be to aim for repeatability like for the airgun case, which for the marine vibrator case means repeating source positions and signatures for all the sweep points.

However, a significantly more challenging problem will be to do a vibrator repeat on an airgun baseline. Vibrator sweeps are fundamentally different from airgun pops both in terms of signature and duration.

We hope that continuous sweeping (inline) and accurate crossline interpolation will allow us to densely sample the wavefield, and thereby allow for 4D interpretation.

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*Figure 2. Crossline source directivity patterns for a monopole (top) and a dipole (bottom) vibrator source in the [30-150] Hz range. The numbers on the x-axis denote frequency in Hz, while the colors indicate signal amplitude. Notice that the dipole has zero vertical energy.*

# Examples

Apart from acquiring geophysical data, the various trials also allowed us to test and verify the overall system performance.

We spent time fine-tuning and verifying the vibrator control algorithms designed to minimize harmonic distortion while accounting for variations in ambient pressure caused by ocean waves/swell. As a result, the vibrator total harmonic distortion is favorable as shown in Figure 3.

We have also developed an accurate source signature estimator (Telling et al., 2023). The estimation of this notional source is then used in the sweep deconvolution that transforms the vibrator data from a continuous signal to the “normal looking” impulsive-source seismic data that we are familiar with.

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Figure 3. Top: Spectrogram of a 5 sec [25-100] Hz sweep recorded on accelerometers mounted on one of the radiators. The lower red line represents the sweep, while the higher order harmonics are visible in green and yellow. Bottom: The harmonics that ty

We have found that the vibrator emission is stable and repeatable, as illustrated in Figure 4 where measurement data from 15 consecutive sweeps are plotted on top of each other. In this figure, the consecutive waveforms are practically identical. This kind of stability is important for future 4D compatibility.

We also have developed a purpose-built real-time QC (Quality Control) system that accurately monitors the output of the vibrators units. All the images in Figures 2, 3 and 4 were created by this QC system.

Finally, we have developed the first iteration of a towing and handling system for the vibrators. One of the main activities going forward will be to engineer reliable vibrator deployment, retrieval, and towing systems. This is a non-trivial engineering problem that thankfully benefits from the years of experience that the seismic industry has in towing equipment through the water.

**Results**

We also point out that to get a good subsurface image it is not sufficient to just build a marine vibrator. What is needed is a complete system that includes towing and handling, positioning and navigation, control system software and hardware and finally seismic processing and imaging.

Our BASS (Broadband Acoustic Seismic Source) system includes all these items. As such, it has required a significant engineering effort from a large team of mechanical, electrical and control engineers.

On the results side, we show the measured and verified acoustic output of the vibrator in Figure 5. These numbers show that a single vibrator outputs significant energy. We believe that by combining 3-6 units, low frequency imaging of even deep pre-salt reservoirs is realistic.

# Conclusions

Depending on the target (reservoir) depth, deploying between 2 and ~6 vibrator units should provide sufficient acoustic energy for seismic imaging. This means that from a geophysical point of view vibrator units can be seen as a one-to-one replacement for an airgun string. Having such a viable alternative to conventional airgun-based sources will be a first for the industry.

Accurate phase and amplitude control allow novel geophysical features like the use of a dipole source, that has the potential to offer efficiency and/or quality improvements compared to conventional airgun-based surveys.

Due to their scalable sound emission, marine vibrators may allow operations in areas where the use of airguns are restricted today.

The development of our vibrator system is still ongoing as seen in Figure 6, and further offshore testing will be required before it is made commercially available. Furthermore, more units need to be produced if we want to have enough acoustic output to image deep pre-salt reservoirs.

Figure 4. Left: 15 consecutive [3-25] and [25-150] Hz sweeps plotted on top of each other. The data used here is the computed Notional source data – based on NFH (Near Field Hydrophones) recordings. Right: A zoom of the waveform showing stability.

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*Figure 5. The confirmed sound level (SL) of one low band and one high band vibrator units.*

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*Figure 6. Two vibrators, one high band (left) and one low band (right) unit before testing.*

# Acknowledgments

Shearwater wants to acknowledge our JIP partners; Equinor, AkerBP and Vår Energy on the BASS vibrator system development. Furthermore, we thank all the Shearwater staff working on the BASS project.

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