Extending seismic bandwidth using the harmonic energy of a marine vibrator source

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Summary

Harmonics in vibrator technology are a common phenomenon and often viewed as undesirable noise. Their presence is widely discussed and treated in the context of land vibrators, with much emphasis dedicated to their removal. However, the discussion on marine vibrator harmonics remains limited. Despite being weaker than the fundamental frequency signal, we show that marine vibrator harmonics can in principle be harnessed to broaden the frequency band of interest for subsurface imaging. This is made possible by our highly reliable marine vibrator source, capable of producing high-fidelity repeatable sweeps, and our accurate notional source estimation method. We demonstrate that harmonics can significantly enhance the frequency band for imaging without requiring any additional processes, achieving the functionality of acting as an additional high-frequency source for imaging the shallow zones.

Introduction

Harmonics are a common and natural phenomenon within vibrator technology, and their occurrence is primarily due to the non-linearities intrinsic to vibrator mechanisms. Traditionally, these harmonics are often perceived as unwanted noise. These harmonics, particularly in the context of land vibrators, are widely studied and discussed. Research firstly focused on the attenuation and elimination of the harmonic signal on land vibrator data beginning from the 1970s, with both hardware and processing approaches (Meunier and Bianchi, 2002). It then gradually shifted to the development of practical techniques aimed at the suppression, and eventually the utilization, of the harmonics to broaden the frequency band (Caporal et al., 2022; Liu et al., 2022).

However, the conversation around marine vibrator harmonics remains relatively limited, despite the rising industry interest in marine vibrators, attributed to their lower environmental impact, precise control over the energy released, and enhanced acquisition efficiency (Halliday et al., 2018). The BASS (Broadband Acoustic Seismic Source) marine vibrator system has been in development for more than a decade. The system, now feature complete, has recently undergone a series of tests.

In this paper, we demonstrate that marine vibrator harmonics can be effectively utilized to extend the frequency band for subsurface imaging. For this purpose, we use data acquired from a recent lake test. Utilization is enabled by a highly reliable marine vibrator source capable of producing high-fidelity repeatable sweeps (Elboth et al., 2022) and by a high-accuracy source signature estimator. First, we introduce our recent lake test acquisition configuration. Then, we illustrate how to estimate the notional source signature and analyze node data for subsurface imaging using just harmonic signals and fundamental frequency

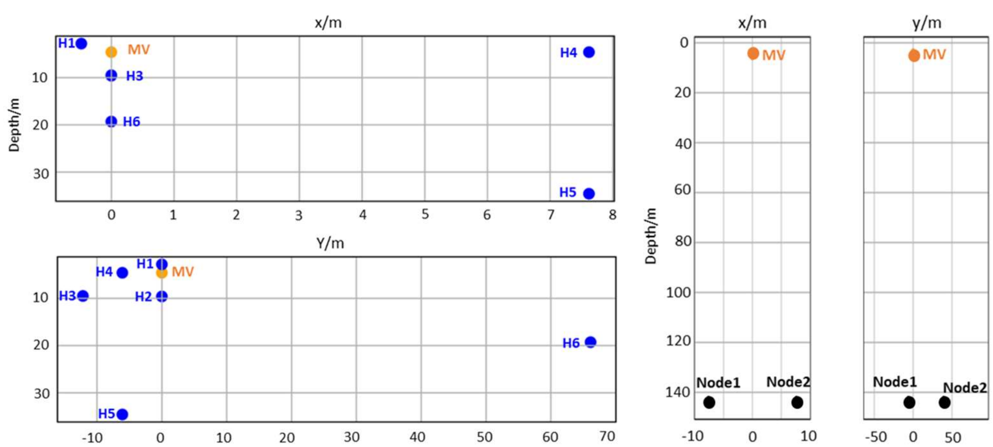

Figure1. Experimental geometry at Seneca Lake showing coordinates of hydrophones H1 to H6, node1 and node2 and the marine vibrator MV. (From Telling et al,. 2023)

signals with harmonics. Finally, we show the processed image to demonstrate the role of harmonics.

Lake test acquisition configuration and selected sweeps

In August of 2022, we conducted a marine vibrator test at Seneca Lake, US (Telling et al., 2023). The lake depth is around 143 metres at the test site. In this test, we placed the marine vibrator 4.6m below the surface of the water in a stationary state and attached NFHs (near field hydrophones) and ACCs (accelerometers) to estimate the notional source signature. We also placed six external hydrophones in the water and two 4C nodes (one of which is used here) below the vibrator on the lake's bed with the geometry given in Figure 1.

During our vibrator testing, we generate and test a variety of sweeps with different frequency ranges. To thoroughly investigate the role of harmonics, we require a portion of the sweep to contain only harmonic energy. We select a low-band sweep spanning approximately 3–25 Hz. This low-band sweep has a duration of 10 seconds and was repeated 10 times in sequence. For comparison, we choose a high-band sweep with a frequency range between 25 and 150 Hz. The high-band sweep lasted for 5 seconds and was repeated 10 times in sequence as well. Both output signals from those two sweeps were acquired using the attached NFH, six external hydrophones, and nodes on the seabed.

The output signal acquired by the attached NFH from a low-band sweep is shown in Figure 2a. Its fundamental frequency energy is between 3 and 25 Hz, and any energy above 25 Hz is a harmonic (Figure 2c). Regarding the output signal (Figure 2b) from the high-band sweep, the energy above 25 Hz consists of both fundamental frequency energy and harmonics. It is worth mentioning that the total harmonic energy is, on average, about 25 dB lower than the fundamental frequency signal (Elboth et al., 2023).

Notional source estimation and node data processing

To get an accurate subsurface stacked trace, we need to conduct an accurate source signature deconvolution. While the electrical input signal that drives the vibration serves as a decent 'pilot' signature, it typically doesn't accurately represent the wavefield released into the water with high precision. Therefore, a good estimate of the notional source signature is needed. In theory, for any source that has a size much smaller than the wavelength, the source signature is directly proportional to the acceleration of the source volume:

$$NS(t) \equiv (\frac{\rho}{4\pi})\frac{d^2V(t)}{dt^2}, \qquad (1)$$

We employ a time-domain iterative method for notional source signature estimation via NFH first proposed by Ziolkowski et al. (1982) for airgun arrays. To estimate an accurate notional source signature for marine vibrators, the

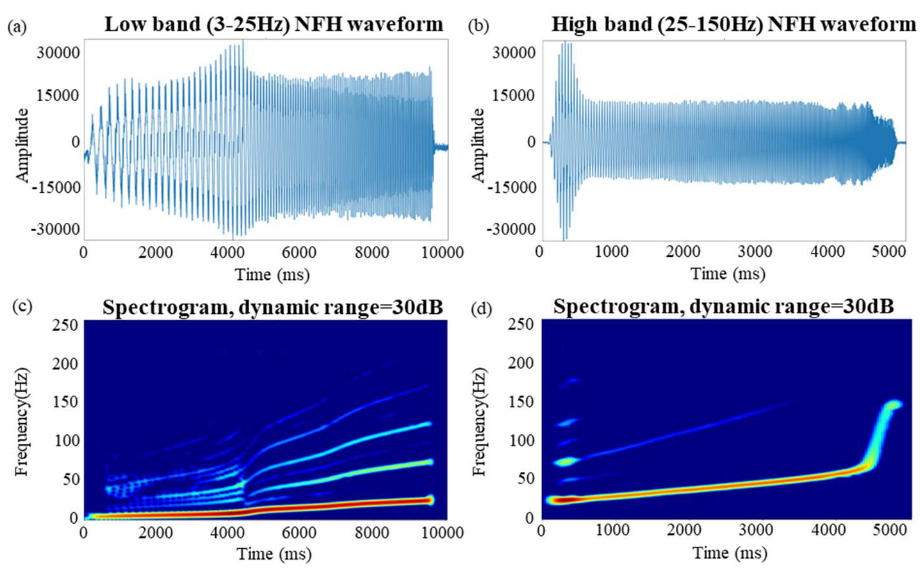

Figure 2 The waveforms of the low-band (3-25Hz) and high-band (25-150Hz) NFH are shown in (a) and (b), respectively; the corresponding spectrograms are shown in (c) and (d)

"clutter" needs to be removed from the NFH data. By clutter, we mean all the signals that the NFH receives that have not come directly from its associated vibrator. For example, in an array of N sources, the clutter at each NFH has 2N-1 components: the direct signals from all the other vibrators and the sea-surface reflected signal from all the vibrators, including its own. After the clutter has been removed from each NFH, using r to represent the distance between the vibrator and the NFH, and c to represent the water velocity, the direct signal received by the NFH at time t can be mathematically expressed as

$$NS(t) = NFH\left(t + \frac{r}{c}\right) \cdot r, \qquad (2)$$

In the marine vibrator case, r can be easily obtained because each NFH is mechanically fixed to its vibrator. If the notional source is calculated from the radiator accelerometers, in principle the NS is simply given by:

$$NS(t) \equiv \left(\frac{\rho}{4\pi}\right)\left(a_1(t) + a_2(t)\right) \cdot \pi R^2, \qquad (3)$$

Where a_1 and a_2 are the radiator accelerations (measured positive outwards) and R is the radiator radius.

To verify the accuracy of the estimated notional source signature from NFH and ACC, we conducted an NS error analysis via forward modelling to external hydrophones H1 to H6 (geometry given in Figure 1) and compare with the received signal in H1 to H6. Figure 3 shows that the NFH spectral errors between predicted data and observed data at external hydrophones from H1 to H6 lie within ± 6dB over the majority of the 3-150Hz bandwidth. Meanwhile, the spectral ratio errors from ACC mostly stay within ± 4dB range throughout the majority of the 3-150Hz bandwidth. Despite efforts to precisely locate source and receivers and minimize environmental noise, it is critical to recognise that positioning errors are possible and that certain interactions and reflections, like those from the lakebed and some objects in the lake, i.e., barge, were not fully considered in our forward modelling. Consequently, these factors have a greater impact on the error analysis for the NFH than on the ACCs measurement. Nevertheless, our predicted results still closely align with the actual received signals, demonstrating the accuracy of our NS estimation.

After notional source signature estimation, the node data from low- and high-band sweeps are then processed separately through PZ calibration, sweep deconvolution, and up-down separation.

Examples

Figures 4a and 4b show the estimated up-going wavefield using low- and high-band data, respectively. Both images are band-passed to 25–150Hz to make them comparable. For better visualization, we arrange both up-going wavefields from low- and high-band sweeps into 10 channels according to the sweep number. As we stated, the fundamental frequency of energy in the low band sweep is between 3 and 25Hz, and any energy above 25Hz consists of harmonics. So the up-going wavefield from the low-band sweep is from harmonic signals only. The energy above 25Hz from the high-band sweep consists of both fundamental frequency energy and harmonics. Figure 4c shows the frequency spectrum of the two images.

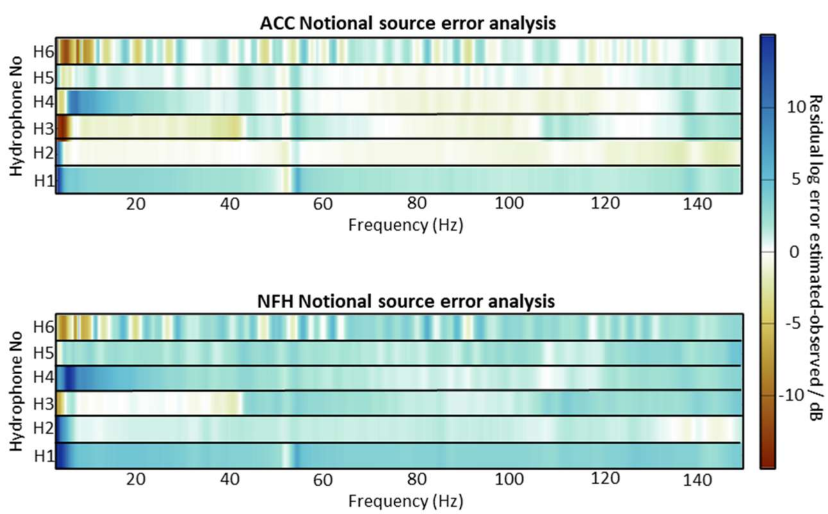

Figure 3: Display of the residual error calculated as difference between the predicted and the actual log power spectra, mapped as a function of frequency. This is shown for the external hydrophones labelled H1 through H6, their positions indicated in Figure 2.

Figure 4 shows that the low-band image (which can be called a harmonics-only image) is consistent with that of the high-band image (obtained from both fundamental and harmonics). This illustrates that, in a marine vibrator seismic survey, the harmonics can play a constructive role in widening the frequency band of the wavefield. It is noteworthy that as the harmoncs are significanly weaker than the fundumental energy, their penetration depth is much smaller. Hence, it is expected that the harmonics will contribute to shallow imaging only. This proof of concept was successful because of the high-fidelity sweep generation by the marine vibrator source and the high-quality estimation of the NSs. NS estimation for a marine vibrator is much more accurate than for a land vibrator for reasons of perfect coupling with the water layer. This improved accuracy paves the way for using harmonics in imaging. Furthermore, we can see that neighbouring traces within the up-going wavefield gathers show very high similarity, indicating a highly repeatable sweep emission.

Conclusions

Marine vibraors bring to the table potential for enhanced acquisition efficiency and a significant advancement in the field of marine seismic acquisition. Historically, harmonics present in the signals emitted by these vibrators have been perceived as noise. However, the findings from our study paint a different picture. In this paper, we demonstrate that it's not only feasible to accurately estimate the harmonic energy associated with the marine vibrator, but also to effectively utilize this energy. The harmonics, contrary to previous understanding, serve to extend the usable bandwidth of seismic data for subsurface imaging. This looks particularly attractive for shallow targets and overburden imaging in general. Our find leverages the capabilities of our developed vibrator to repeatedly emit designed sweeps and our notional source estimation, which includes not just fundamental frequencies but all orders of harmonics. Moreover, the absence of severe coupling issues in the marine environment further supports the utilization of harmonics. However, while these findings are promising, additional research is required to evaluate the feasibility of this approach when the marine vibrators are operated in an array and under tow. These promising preliminary results thus provide a new direction for future research in marine vibrator data processing.

Acknowledgments

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Upgoing wavefield from low and high band sweep and spectrum

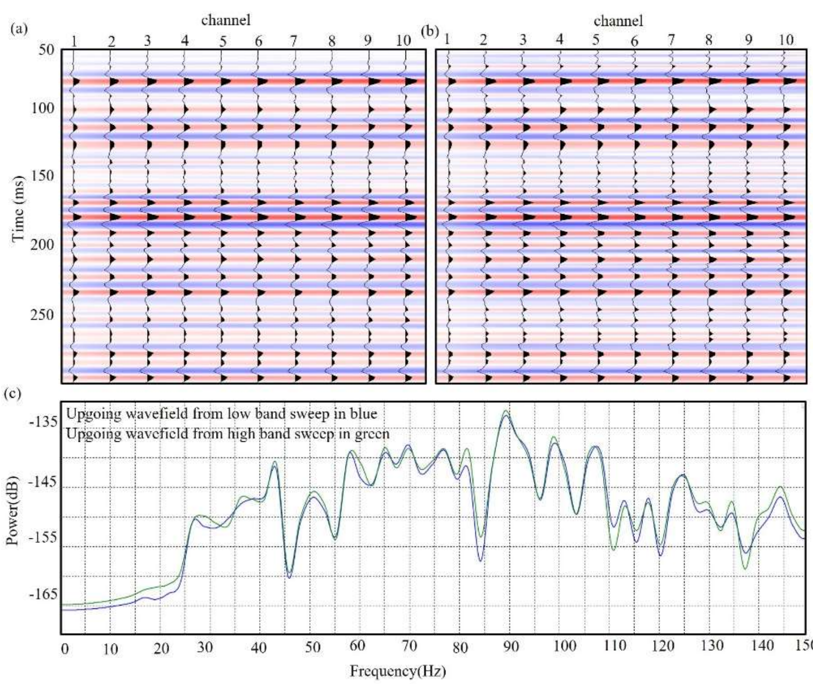

Figure 4 Top row: The up-going wavefields (band passed 25-150Hz) obtained from low-band (3-25Hz) a) and high-band (25-150Hz) b) sweeps. Bottom row: The frequency spectrum from a) and b).

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