Marine Vibrator Concepts for Modern Seismic Challenges

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SUMMARY

Aside from historical issues of mechanical durability and efficiency, the design of marine vibrators (MVs) for towed streamer operations are confronted by several practical challenges to their different possible applications: 1. Alternatives to conventional air gun arrays for flexible and creative acquisition geometries, 2. Low power alternatives to air gun arrays for environmentally sensitive applications, and 3. High power ultra-low frequency sources specific to Full Waveform Inversion (FWI) optimization.

One relevant consideration to MV operations is the volume of water that must be displaced per cycle to achieve a desired Sound Pressure Level (SPL); increasing exponentially as the frequency of interest decreases, and becoming significant at frequencies less than about 5 Hz. This is particularly relevant for FWI optimization as the frequencies of interest are in the range of 1-6 Hz. Another consideration is that ultra-low frequency output theoretically benefits from deeper towing enhanced by the well-known free-surface ghost effect, but in practice, deeper towing is confronted by an air spring effect that increases the force required per cycle to generate a desired SPL, and is due to the surrounding hydrostatic pressure at depth.

Environmental motivations to develop low power vibrator concepts are driven by regulatory restrictions upon received SPL and Sound Exposure Level (SEL), and we demonstrate how low power MVs can be configured to yield low SPL and SEL metrics without compromising geophysical performance—in contrast to the use of air gun arrays with few elements. MVs enable independence from large compressors and may be more easily deployed in spatially distributed geometries than air gun arrays. We present examples of flextensional MV development verified by numerical modelling, tow tank testing, and field verification; collectively supporting the principles discussed herein.

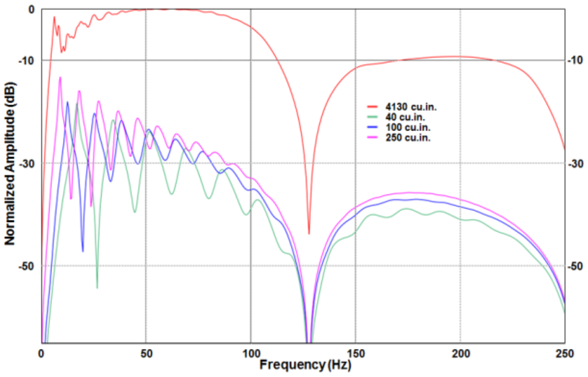
Key words: Marine vibrator, air gun, environment, FWI.

INTRODUCTION

Marine seismic sources used in exploration are typically impulsive air guns arranged in arrays and fired either simultaneously or with small time delays to reduce the free-surface ghost effects upon the emitted source wavefield (e.g. Cambois et al., 2009; Parkes and Hegna, 2011). Whilst most attention over the past decade has been on 'broadband' source design and real-time monitoring (e.g. Tabti et al., 2017), industry attention is firmly turning to the impact of air guns upon marine animals and their environment. Ideally, air gun arrays can be flexibly operated in ways that mitigate the received sound levels in a frequency-dependent manner, for example, operated with lower zero-peak output, reduced output at frequencies above about 100 Hz, with slower rise times to peak output of each shot, and so on. Each of these ambitions has met limited success. It is also the case that more flexible towing geometries are desired for seismic sources in order to more uniformly sample the azimuth-offset parameters of the recorded seismic wavefield for each shot, improve near offset coverage for high resolution shallow imaging, and break the shackles of large vessels carrying large air compressors necessary for air gun operations in multi-vessel survey designs. In each scenario above it is argued below that towed marine vibrators (MVs) offer potential solutions.

Although the zero-peak output of air gun arrays roughly scales in proportion to the number of air guns used, the use of a small number of air guns to reduce output is challenged by the necessity to mitigate unwanted reverberating bubble energy with 'array tuning'—By using air guns of several different volumes that are spaced optimally relative to one another, air gun arrays may be 'tuned' to increase the amplitude of the primary peak and simultaneously decrease the relative amplitudes of the subsequent bubble pulses. The emitted source wavefield is also strongest in the vertical propagation direction (Dragoset, 2000). As illustrated in Figure 1, the frequency spectrum of the emitted source wavefield is band-limited (about 7-120 Hz at the 12 dB down points), compromised by bubble energy, and the source wavelet is far from the Dirac-type wavelet that would correspond to a white amplitude spectrum. Furthermore, exposure to impulsive sounds can potentially yield various behavioural effects upon marine animals as a function of duration and intensity, and in the worst cases, can lead to mechanical fatigue of the inner ear resulting in temporary or permanent threshold shifts. Although solutions are emerging to reduce high frequency air gun output by controlling air flow during firing (e.g. Coste et al., 2014), the zero-peak sound pressure level (SPL) output of air gun arrays is typically of the order of 240-250 dB at 1 m distance, and the idea of a simple universal solution to limit or reduce array output without loss of data quality and that would yield any measurable benefit to the marine environment is impracticable and not supported by current best available scientific data (IAGC, 2014).

In contrast, the use of MV sources rather than air guns is expected to reduce most types of environmental impacts in all habitats and environments. Behavioural and auditory effects of most types are expected to be less with MVs, regardless of water depth or other environmental conditions (LGL and MAI, 2011). As discussed below, marine vibrator units emit a transient source wavefield with low power and flexible control of frequency bandwidth. Full bandwidth seismic acquisition can be pursued without any air bubble considerations, so the source arrays may only contain a small number of MV units. With freedom from air compressors, electrical MV units offer significant flexibility and opportunities to meet a variety of environment, operational and geophysical ambitions.



Volume (in^3)	4130	40	100	250
Zero-Peak SPL (dB re 1µPa at 1 m)	241.0	227.6	230.4	232.4

Figure 1: Comparison of frequency spectra for three individual air guns (40 in^3, 100 in^3, and 250 in^3) and a 4130 in^3 air gun array at 6 m depth. Note the complementary notches in the amplitude spectra associated with the different bubble periods of each air gun. The notch at about 125 Hz on all spectra correspond to the free-surface ghost notch for 6 m towing depth. The table plots the maximum zero-peak SPL values in the near field at 1 m distance computed for each respective array / air gun (refer also to ISO, 2017).

FUNDAMENTAL MARINE VIBRATOR CONSIDERATIONS

Flextensional shell marine vibrators such as considered here have an elliptic shell wherein the longer, major axis of an ellipse is set into vibration by a driving force, for example an electro-dynamic driver, and the length of the shorter, minor axis will also vibrate, but with a much larger amplitude; thereby the outer shell moves back and forth by flexing to generate acoustic energy. Furthermore, flextensional shell sources may be designed with a low fundamental resonance frequency (see below) so that the shell's dimensions are small compared to the wavelength in water, thereby allowing the shell to radiate sound omnidirectionally.

Figure 2 shows two relevant considerations when using MVs to generate low frequency amplitudes: 1. The volume of water that must be displaced per cycle, and 2. The 'air spring effect' upon the resonance frequencies (note in Figure 2a how an exponentially greater volume of water must be displaced per cycle to generate a given output at decreasing frequencies e.g. more than 1 m^3 at 2 Hz). High amplitude ultra-low frequency amplitudes can either be generated by using a very high displacement of the surface of one MV unit or by distributing a smaller displacement over the surface of several MV units. Low frequency output will also be enhanced overall by both increasing the towing depth to exploit the source ghost effect and designing a configuration that creates low resonance frequencies, however, both ambitions are challenged by the air spring effect. In order to achieve a given level of output in the water, a marine vibrator typically needs to undergo a change in volume. In order to work at depth while minimizing structural weight, the marine vibrator must be pressure balanced with external hydrostatic pressure. As the internal gas (e.g. air) in the marine vibrator is increased in pressure, the bulk modulus (or 'stiffness') of the internal gas also rises. Increasing the bulk modulus of the internal gas also increases the air-spring effect within the marine vibrator. As used herein, the term 'air spring' is defined as an enclosed volume of air that may absorb shock or fluctuations of load due to the ability of the enclosed volume of air to resist compression and decompression. Increasing the stiffness of the air in the enclosed volume increases the air-spring effect and thus the ability of the enclosed volume of air to resist compression and decompression. This increase in the air-spring effect of the internal gas tends to be a function of the operating depth of the source. Further, the stiffness of the acoustic components of the marine vibrator and the internal gas are the primary determining factors in the marine vibrator's resonance frequency. Accordingly, the resonance frequency generated by the marine vibrator may undesirably increase when the marine vibrator is towed at depth.

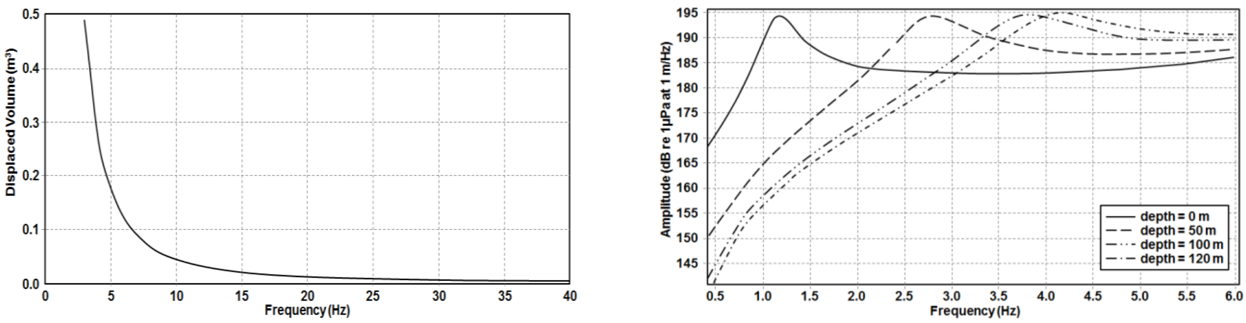


Figure 2: (Left) Volume of water that must be displaced per cycle to generate an output of 200 dB re 1 µPa/Hz; (Right) Amplitude vs. frequency as a function of towing depth: Resonance frequency increases with increasing towing depth.

Figure 3 shows how by careful design, resonances may be introduced into the lower end of the frequency spectrum so that low frequency acoustic energy may be generated more efficiently. At resonance, the imaginary (reactive) part of the impedance is cancelled, and the marine vibrator may be able to efficiently transmit acoustic energy into the body of water (Crocker, 1998). The first resonance frequency is due to the interaction of the outer shell acting as a spring and the second resonance frequency is achieved due to the spring element itself.

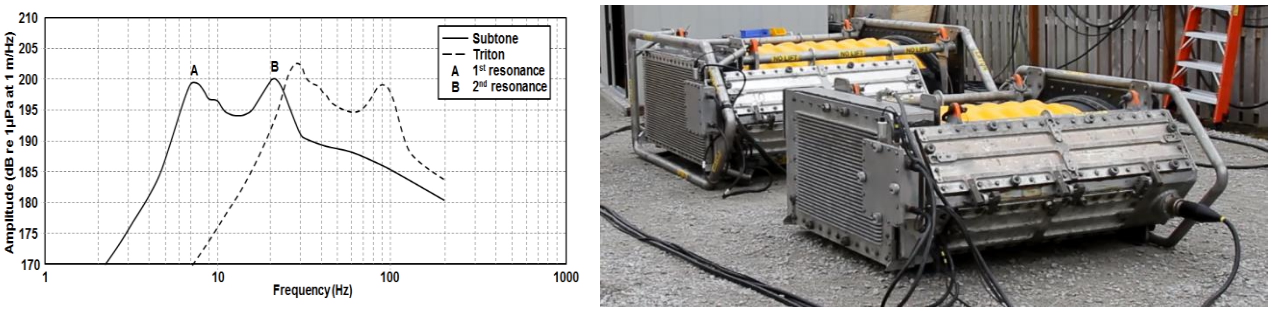


Figure 3: (Left) Contiguous amplitude spectra for the Subtone and Triton flextensional marine vibrator units. Note the two resonance frequencies ('A' and 'B') for each spectrum; (Right) MV units ready for testing.

Hydrodynamic towing stability needs to be considered for MV operations, particularly if the MVs are not suspended from surface floats in the manner of conventional air gun arrays. Figure 4 shows a conceptual towing configuration along with numerical and tank testing simulations. The flextensional MV concept shown here can be adapted to low impact environmental surveys, arrays of many MV units, or designs that explicitly target ultra-low frequencies in the 1-7 Hz range (see below).

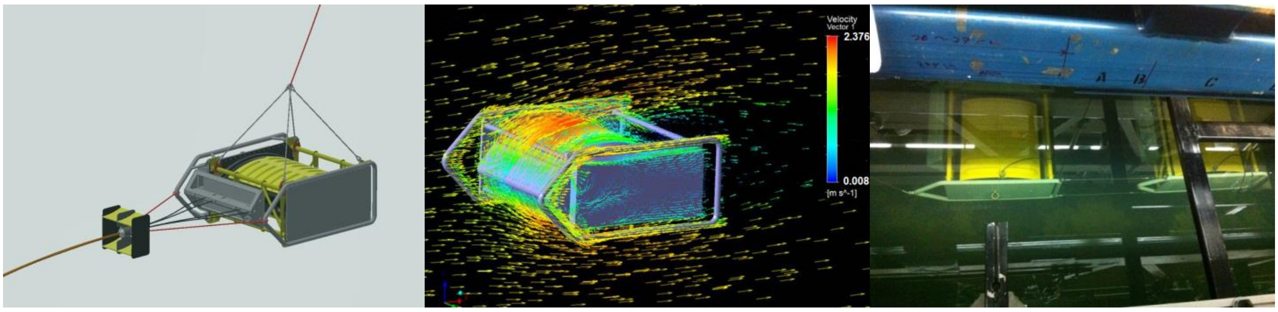


Figure 4: (Left) Conceptual towing configuration; (Middle) Numerical modelling of water velocity around the MV unit at 4.5 knot towing speed; (Right) 1:4 models undergoing tow tank testing.

LOW ENVIRONMENTAL IMPACT AND OPERATIONAL FLEXIBILITY

As discussed earlier, there is minimal scope for reducing the output of an air gun array by modifying the operating pressure or the total air volume of the array. Modifying the number of elements or the dimensions of the array would result in an undesirable accentuation of high frequency noise and compromise the quality of seismic data with a loss of low frequency amplitudes (IAGC, 2014). In contrast, Figure 3 illustrates how only two flextensional marine vibrator units can emit a seismic wavefield that has reasonably uniform amplitude in the 5-100 Hz range—due to the contiguous and overlapping frequency output from the two units, and the maximum output is about 206 dB re 1 μPa/Hz. The application of iterative learning control (ILC) on the sweep signal (Tenghamn, 2006) enables frequency-dependent customization of the source wavefield and mitigation of harmonic energy in a highly-repeatable manner. Furthermore, the harmonic output above 100 Hz decays rapidly due to the resonance characteristics of the units, being more than 40 dB down above 150 Hz. In contrast, two air guns would have an amplitude spectrum characterized by strong bubble artifacts at low frequencies and higher output (and SEL) at high frequencies (refer to Figure 1).

In a synthetic modelling study of received sound levels from air gun and MV arrays, Duncan et al. (2017) show that overall, MV produced lower broadband SELs, especially at long range, and lower peak pressure, especially at short range, than air guns. There have been almost no direct studies of the physiological and behavioral effects of MV operations, so most commentary upon environmental compliance is based upon comparative SPL and SEL metric performance vs. air guns.

Note that the use of a MV array with 'comparable output' to conventional air gun arrays, as was used in Duncan et al. (2017), is undoubtedly influenced by the dogma enforced by decades of air gun array design and 'tuning'. The use of MV arrays with only a small number of MV units should be feasible without unacceptably compromising seismic image quality, and with received SPL and SEL levels much lower than observed for air gun arrays. High duty cycles with MV sweeps need to be considered in the context of masking effects for marine animal communication, but flexibility exists with respect to sweep design for reducing SPL, SEL, and the cumulative SEL (SEL_{cum}) for many consecutive sweeps or operations over several hours or days. For example, by comparison to simple linear sweeps, appropriate phase encoding of MV sweeps may enable operationally efficient simultaneous sweeps from several MV units, as well as potentially yielding reduced SEL/SEL_{cum}, despite having 100% duty cycle.

From the perspective of operational flexibility, no air compressors are required for internal pressure equalization when towing MV units at depths comparable to air guns (and air spring effects can be ignored), so small and lower cost source vessels can be considered for multi-vessel operations such as wide-azimuth (WAZ) and full-azimuth (FAZ) towed streamer surveys, ocean bottom node (OBN) surveys, and so on. MVs can also deployed as stationary units on the seafloor in very shallow water (e.g. transition zone surveys) or towed at very shallow depths without compromising the integrity of the source wavefield in the manner of air guns being fired at very shallow depths. The industry vision of dispersed sources arrays (DSAs: see Berkhout et al., 2017) using autonomous vessels may also be more readily achieved using MV sources.

THE PURSUIT OF ULTRA-LOW FREQUENCIES

The amplitude of air gun output decays below about 7 Hz at about 16 dB per octave (Dellinger, 2016), and no configuration of large volume, shallow tow air gun array designed to improve ultra-low frequency output has proven practical. Dellinger et al. (2016) present a large MV concept capable of emitting SPL in the 1-8 Hz frequency range. The unit was towed at about 60 m depth to exploit the free-surface ghost effect at ultra-low frequencies, and the internal volume is very large to reduce the air spring effect. The two challenges identified in Figure 2 are most relevant for very deep towing with high displacement objectives per cycle. If realized, however, an ultra-low frequency source could facilitate stable inversion with minimal cycle-skipping in Full Waveform Inversion (FWI), may mitigate the 'low frequency gap' confronting quantitatively accurate seismic inversion for elastic impedance attributes, and would enable signal penetration for more robust deep earth imaging.

CONCLUSIONS

By careful design, towed marine vibrator concepts are being developed that exploit resonance frequency physics to optimize efficiency, and that overcome the historical dogma driven by air gun array tuning that many source elements are necessary to yield a smooth and contiguous amplitude spectrum in the seismic frequency range of interest. Moreover, the use of iterative learning control (ILC) on the sweep signal enables frequency-dependent customization of the source wavefield and mitigation of unwanted harmonic energy in a highly-repeatable manner. Consequently, marine vibrators may present an attractive opportunity to significantly reduce the environmental impact of marine seismic surveys, enable flexible source configurations to optimize survey efficiency, and resolve long-standing challenges to the output of large amplitudes in the 1-7 Hz frequency range.

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