Modelling of marine vibrator data

Introduction

Marine seismic vibrators have been considered as environmentally friendly sources for seismic exploration since the early 1970’s (e.g., Broading et al., 1971). Recently they have been considered as a serious contender to air-gun arrays. While their reduced environmental impact is highly attractive (Southall et al., 2007; LGL & MAI, 2011), further drivers are the ability to precisely control the characteristics of the released energy and the potential survey efficiencies that can be obtained (Halliday et al., 2018).

Synthetic seismograms are a useful tool for the evaluation of equipment specifications and data processing algorithms. Due to the long time duration of sweeps used with marine vibrators, the source motion needs to be accounted for when modelling such data, however, incorporating source motion in conventional seismic modelling tools is cumbersome. There have been attempts to modify existing modelling methods, such as finite difference (FD) programs, to account for source motion (Asgedom et al., 2020). Dellinger and Díaz (2020) proposed a source compression strategy along with employing reciprocity to model the source motion effect for vibratory sources. However, the approach that we describe here does not need any modification to conventional modelling methods. We consider impulsive source response data for closely-spaced regular source and receiver locations, consisting of a set of synthetic traces generated with conventional finite difference modelling methods. The synthetic impulsive source data are then used as input to generate marine vibrator data for the desired acquisition setup and sea surface state. The method we describe was used by Laws et al. (2019), but is not thoroughly described therein.

Synthetic impulsive source response

The key ingredient of this modelling approach is a high resolution synthetic impulsive source response of the subsurface model. It can be calculated using highly accurate numerical methods, such as finite difference methods, for closely spaced and regular source and receiver locations. Special attention must be paid to the spatial spacing of the source and receivers to avoid aliasing of the modelled data up to the desired frequency. This is essential as further modelling steps rely on the input data being un-aliased. Although preparing the synthetic impulsive source data is computationally demanding, the subsequent modelling of a wide range of marine-vibrator scenarios is affordable.

Forward modelling approach

Once the impulsive source data are available, the acquisition setup and perturbation effects can be included. In this section, we describe how this is carried out for an ocean bottom node (OBN) acquisition, however extension to towed streamer cases is straightforward. For any given sweep the modelled data is calculated from a spatial window of impulsive sources within the vicinity of the vibrator location. The selected data are transformed to the local slowness domain $D(f, p_x, p_y)$ and for the $n$th marine vibrator, emitting sweep $S_n(f, T)$ as it is moving through the positions $[x_n(T), y_n(T)]$, the generated data is given by (Halliday, Research report, 2018):

$$d(f, x_n(T), y_n(T)) = \sum_{T_1}^{T_2} S_n(f, T) \sum_{p_x, p_y} g_n(f, p_x, p_y, T) D(f, p_x, p_y) e^{-2\pi f (p_x x_n(T) - p_y y_n(T))}, \quad (1)$$

where $f$ represents temporal frequency, $p_x, p_y$ are the horizontal slownesses in $x$ and $y$ directions respectively, $T$ indicates time, $T_1$ and $T_2$ are start and end time of the sweep and $g_n = 1 - r e^{-ik z_n}$ is the ghost operator with $r$ as the sea-surface reflection coefficient, $k$ as the vertical wavenumber and with $z_n$ indicating the depth of the $n$th vibrator.

Figure 1 shows a schematic of the main steps for the forward modelling of a common-receiver gather of a typical OBN survey. To model a trace for any source location, the neighbouring input traces within
a certain radius are selected. This radius must cover the expected distance that the source boat will move during the sweep time, plus extra traces for padding (grey zone in Figure 1a). The selected subset of data is then transformed to the tau-p domain using a 3D radon transform. For higher efficiency and since the input impulsive data are regularly spaced, we use an efficient chirp modulation-based radon transform (Andersson & Robertsson, 2019), which is proven to be a significantly faster transform than the conventional discrete radon transforms.

**Figure 1** Schematic description of using synthetic impulsive source data to generate marine vibrator data. (a) Regular locations of the impulsive source data (open circles) and selected subset of data (solid box) to be transformed to the (b) tau-p domain. (c) The reconstructed data with very high resolution used to incorporate source motion effect. (d) Output modelled data at the desired location.

In the 3D tau-p domain (Figure 1b) the source is redatumed to the desired depth and the corresponding sea-surface wave-height is used to model the source-ghost at all propagation angles. The tau-p model is then transformed to the data domain and since there is no aliasing, high resolution data with closely spaced source locations can be reconstructed (Figure 1c). As shown by equation 1, this reverse transformation allows incorporation of the source motion by splitting the vibrator sweep into portions according to the sweep length and boat speed. The segments are then convolved with the reconstructed traces along the direction of boat movement, before stacking to produce a modelled trace at the desired location (Figure 1d).

**Modelling example**

We created a synthetic dataset for an OBN acquisition setup using the SEAM (Society of Exploration Geophysicists (SEG) Advanced Modelling, www.seg.org/seam) Phase 1 model. A portion of the model (away from the main salt body) was selected, and the seabed is at a depth of approximately 1900m. Nodes were placed just above the seabed and the FD generated impulsive source data has a maximum frequency of 64Hz with 10m regular source spacing and source depth of 10m. The 10m spacing of impulsive source data provides us with unaliased input data.

Figure 2 shows a time-slice from the input synthetic impulsive source data (Figure 2a) and the reconstructed data with 1m spacing (Figure 2b), which are generated as intermediate products as described above. We further include the source-ghost and source motion effects for a single vibrator unit at 20m depth and a boat speed of 2.3m/s (4.47kn). The source spacing of the output modelled gathers is 20m.

Figure 3a shows impulsive source data used for modelling of a common-receiver gather. To see the impact of both source-ghost and source motion in case of a 3Hz - 60Hz linear sweep 5s long, (Figure 3b) shows the result of modelling without source-ghost and motion, (Figure 3c) with source-ghost only and (Figure 3d) with both ghost and motion effects. To better see the impact of the source motion, the difference between Figures 3c and 3d is shown in Figure 3e. Corresponding frequency-wavenumber (f-k) spectra in the lower row of Figure 3 clearly show presence of a ghost notch at 37.5Hz at vertical incidence as well as the source motion effect, which gets stronger with increasing event dips.
One of the key advantages of the marine vibrator is the ability to fully control the phase of the sweep as described in Laws et al. (2019). It is therefore possible to create a directional source by operating two vibrators in close proximity and with opposite phases. Laws et al. (2019) describe the significant benefit of combining directional and omni-directional sweeps to interpolate recorded data between neighbouring source-lines. The proposed modelling approach has the flexibility to generate data for both omni and directional sources. Figure 4 shows time slices from the modelled common-receiver gathers for the omni (Figure 4a) and directional sources (Figure 4b). Strong wavefield energy in the $x$-direction (normal to sail line direction) is obvious in the time slice of the directional source data.

**Conclusion**

We discuss an effective and flexible approach to creating synthetic data for marine vibrators. The proposed approach uses un-aliased impulsive source synthetic data as input which allows us to reconstruct the output data at desired locations without difficulty. Acquisition, environmental and wave propagation effects such as ghost and source motion can be easily incorporated. Generating data for omni and directional sources is possible using the same impulsive source input.
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Figure 4 A time-slice from the modelled common-receiver gather without sweep, ghost and source motion effects for (a) an omni-directional source and (b) a directional source. The green triangle indicates receiver location.

References