Th_P05_10

Marine Vibrator Sources: Motion Correction, Deghosting and Designature

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Summary

Traditional marine seismic sources such as compressed air sources are impulsive and thus deliver their output almost instantaneously. This implies that the source output can be assumed to be stationary and the associated source motion neglected during processing. However, with increasingly strict environmental regulations and demand for efficiency and control of the source output, alternative sources that can meet these requirements are currently being developed. Marine vibrators are among the most promising candidates for such sources since they are inherently non-impulsive and controllable. The output is distributed over time, typically as sweep signals in the order of a few seconds in duration. Consequently, marine vibrators are highly susceptible to source motion effects. In this paper, we demonstrate how to properly handle these motion effects and perform source deghosting and designature in one operation. The input data is modeled using moving sources following the Marine Vibrator Joint Industry Project (MVJIP) source specifications.
Introduction

The effects of motion on marine seismic data from a vibrator source have significant consequences (Dragoset, 1988; Hampson and Jakubowicz, 1995; Qi and Hilterman, 2016). The current industry standard method for source motion correction is based on spatiotemporal filtering, or frequency-wavenumber (FK) domain division. This method assumes that moving source marine vibrator data can be modelled using the convolutional model (Hampson and Jakubowicz, 1995). However, this model intrinsically assumes that the source signatures are the same from source-to-source. In addition, the acoustic medium and the sea surface are also assumed to be invariant. In this work, relying on acoustic reciprocity, we derive a generalized expression for modelling seismic data from moving marine vibrator sources. Moreover, this formulation can also be used to perform deconvolution, which includes source motion correction, deghosting and designature, in one operation without any restriction on variations in the source signature. The convolutional model based method performs deconvolution by FK domain division whilst our formulation uses frequency-space (FX) domain inversion. Therefore, for computational efficiency reasons, we show that deconvolution by inversion may be replaced by first applying source-to-source correction to the input data followed by FK division. The results are verified using synthetic data modeled with notional source signatures derived from measured nearfield hydrophones of recently developed PGS marine vibrator sources. To make the simulations as realistic as possible, noise measured in the field was also added to the modeled data.

Method and Theory

Provided the source wavefield is recorded in the field (or modelled using the notional sources), it is possible to utilize acoustic reciprocity (Fokkema and van den Berg, 1993) to couple the source wavefield with the subsurface reflectivity (free of source motion, signature, array and ghost effects) to generate the up-going pressure wavefield (see Fig. 1). This can be written for a single angular frequency $\omega$, source locations $(x_0, z_0)$, receiver locations $(x_6, z_6)$ and virtual source/receiver locations $(x, z)$ as

$$P_{\text{up}}(x_6, z_6, \omega|x_0, z_0)S_d(\omega) = -2i\omega\rho \int_{-\infty}^{\infty} V_{dz}(x, z, \omega|x_0, z_0)R(x_6, z_6, \omega|x, z)dx,$$

where $P_{\text{up}}$, $V_{dz}$, and $R$ are the up-going pressure, the down-going vertical particle velocity (or the source wavefield), and the subsurface reflectivity (generated with the desired source signature $S_d$) wavefields, respectively. Moreover, $\rho$ is the mass density, and $i = \sqrt{-1}$. The expression in Eq. 1 is general and has no assumptions regarding the source wavefield and the subsurface reflectivity.

![Figure 1 Sketch depicting up-going pressure (left), source wavefield (middle) and the subsurface reflectivity (right).](image)

Discretizing the integral in Eq. 1 and considering a single frequency, a single receiver, $N_s$ sources, and $N$ virtual sources/receivers, we obtain the following linear system of equations:

$$P_{\text{up}}S_d = -2i\omega\rho V_{dz}^{dn}r,$$

where $P_{\text{up}} \in \mathbb{C}^{N_s \times 1}$, $V_{dz}^{dn} \in \mathbb{C}^{N \times N_s}$, and $r \in \mathbb{C}^N$. If the inverse of $V_{dz}^{dn}$ exists, it is possible to obtain the subsurface reflectivity using the following relation:

$$r = \frac{-S_d}{2i\omega\rho} [V_{dz}^{dn}]^{-1}P_{\text{up}},$$

where $[\ ]^{-1}$ is the mathematical inverse operator. We now assume $V_{dz}^{dn}$ is laterally invariant, which is equivalent to having a flat sea surface, source-to-source signature invariance and a laterally homogeneous medium. In this scenario Eq. 1 reduces to (Söllner, 2016):
The receivers are stationary and placed at a depth of 25m. In our first case, we demonstrate deblending. The receivers are stationary and placed at a depth of 25m. In our first case, we demonstrate note that in real data acquisition, such a shot point interval can only be achieved after performing sources are activated at a lateral spacing of 6.25m and are moving with a constant velocity of 2.7m/s. In the modelling, the frequency source (35 – 100 Hz) and at 20m a low frequency source (1 – 45 Hz). In the modelling, the high moving and stationary sources. The red dotted lines in (c) and (d) denotes the signal cone. Figure 2 Examples

We first illustrate the effects of motion on marine vibrator seismic data by performing 2D numerical modelling. Seismic sources moving with a realistic vessel speed of 2.7m/s were modelled. The notional source signature is a 5s long linear sweep inverted from a field measurement. For all time-space plots by multiplying each trace with time. The results of Figs. 2b – d attest to the fact that motion effects of marine vibrator sources are significant and manifest mainly as a phase distortion. Note that for the purpose of plotting, all 2D wavefields were multiplied with \( \sqrt{\omega} \) to simulate a 2D-to-3D correction and geometric spreading correction for all time-space closely. Equation 4 is the convolutional model and it can be used to model the up-going pressure wavefield from moving marine vibrator sources only when \( \hat{V}_z^{dn} \) is laterally invariant. However, if only the source signature changes from source-to-source, the up-going pressure wavefields from Eqs. 1 and 4 can be linked to each other using source-to-source time varying filters \( f(x_r, z_r, t|s_x, s_z) \). This time varying filtering, needed because of the inherent motion, is given as:

\[
\int_{-\infty}^{\infty} p_{up}(x_r, z_r, \omega|s_x, s_z) f(x_r, z_r, t - \tau|s_x, s_z) d\tau = \hat{p}_{up}(x_r, z_r, t|s_x, s_z).
\]

A time stationary estimate of the filter \( f \) can be obtained when the source-to-source variation and the desired invariant source wavefield are known. This allows us to write:

\[
F'(x_r, z, \omega|s_x, s_z) = \frac{\hat{V}_z^{dn}(x_r, z, \omega|x_x, z_x)}{V_z^{dn}(x_r, z, \omega|x_x, z_x)}.
\]

Here, it is pertinent to note that obtaining \( F' \) using Eq. 6 is computationally efficient but it is not the correct way of finding the time varying filter \( F \) that is needed in Eq. 5. Nevertheless, after applying source-to-source correction using \( F' \), we can then utilize Eq. 4 to obtain an estimate of the subsurface reflectivity as:

\[
R'(x_r, z_r, \omega|s_x, z_x) = \frac{\hat{p}_{up}'(x_r, z_r, \omega|k_s, s_z) S_d(\omega)}{-2i\omega \hat{p}_z^{dn}(x_r, z, \omega|k_s, s_z)}.
\]

Examples

We first illustrate the effects of motion on marine vibrator seismic data by performing 2D numerical modelling. Seismic sources moving with a realistic vessel speed of 2.7m/s were modelled. The notional source signature is a 5s long linear sweep inverted from a field measurement. The modelled up-going pressure wavefield from a moving source at 6m depth with the source output adjusted to the Marine Vibrator Joint Industry Project (MVJIP) (Feltham et al., 2017) criteria is shown in Fig. 2a. The difference between the moving and stationary source up-going pressure wavefields is shown in Fig. 2b and the corresponding amplitude and phase differences are shown in Figs. 2c and d, respectively. The results of Figs. 2b – d attest to the fact that motion effects of marine vibrator sources are significant and manifest mainly as a phase distortion. Note that for the purpose of plotting, all 2D wavefields were multiplied with \( \sqrt{\omega} \) to simulate a 2D-to-3D correction and geometric spreading correction for all time-space plots by multiplying each trace with time.

Figure 2 Modelled up-going pressure wavefield: (a) Moving source. (b) The residual between moving and stationary source multiplied by 2.5. The amplitude ratio (c) and phase difference (d) between moving and stationary sources. The red dotted lines in (c) and (d) denotes the signal cone.
the effects of uncertainty in the source signatures. The uncertainty considered here is according to the MVJIP specifications: ±4º in phase and ±10% in amplitude error. Moreover, we have added field recorded noise in the modelled up-going pressure wavefield data (see Figs. 3a and b). The perturbation in the up-going pressure data is the result of introducing random uncertainty (with maximum deviation of ±4º in phase and ±10% in amplitude) in the source signatures which results in the spreading of the signal energy outside the signal cone in the FK domain (see Fig. 3b). The reference subsurface reflectivity is shown in Figs. 3c and d. Observe that all the energy in the reference subsurface reflectivity lies within the signal cone since there is no uncertainty in this data (cf. Fig. 3d).

The up-going pressure data with the uncertainty included is used as input to the deconvolution based on inversion and FK domain division. The source wavefield for deconvolution was prepared using a reference notional source signatures without any knowledge of the uncertainty in the measured data. Both deconvolutions were stabilized by adding small numbers to the source wavefield – at the diagonal for the inversion and in the denominator for the FK domain division. The results of the inversion based deconvolution are shown in Fig. 4a and its corresponding difference from the reference subsurface reflectivity in the FK domain is shown in Fig. 4b. Similarly, the results of the FK domain division (see Fig. 4c) and its corresponding difference from the reference subsurface reflectivity in the FK domain is shown in Fig. 4d. From these results, one can infer that in the presence of uncertainty in the data, both inversion and FK domain division give similar results except at the edges of the signal cone. This is intuitive, since the former assumed no uncertainty in the measured data (as the source wavefield was fluctuation free) while the latter expects that the measured data are the same from source-to-source. Note also that the residual in Figs 4b and d quantifies the error as a result of random uncertainty in the source signatures as dictated by the MVJIP criteria.

In addition to the uncertainty in the data, we now introduce a random source-to-source variation of ±10º in phase and ±3dB in amplitude. However, we consider that the source-to-source variation is known – the corresponding source wavefields were prepared having the same variation. Therefore, we can utilize the source wavefields from the varying sources to perform inversion (see Figs. 5a and d), FK domain division (see Figs. 5b and e), and FK domain division after source-to-source correction of the up-going pressure data (see Figs. 5c and f). The inversion result in Fig. 5d shows similar residual as that of Fig. 4b. This implies that the inversion method can handle the source-to-source variation as long as the corresponding source wavefield is known. The FK domain division expects no source-to-source
variation and hence results in a large error (see Fig. 5e). However, when the source-to-source varying source wavefield is known, we can prepare source-to-source correction filters using Eq. 6 and apply these filters to the measured up-going pressure wavefield. The FK domain division after source-to-source correction results in a significantly reduced residual error (see Fig. 5f).

![Figures 5](image)

**Figure 5** Top panels show the time-space domain plots for the recovered reflectivity after inversion (a), FK domain division (b) and FK domain division after source-to-source correction (c). The lower panels (d-f), show the corresponding differences relative to the modelled reference in the FK domain.

**Conclusions**

Source motion effects from marine vibrators have a significant impact on seismic data. In this work, we have derived an acoustic reciprocity based method for modelling seismic data from moving marine vibrators. The same approach was also used to derive an inversion based method for simultaneously performing source motion correction, deghosting and designature. Moreover, we have shown that the conventional methods that use FK domain division are inherently limited to the case where the source wavefield is laterally invariant. In situations where source-to-source variations can be estimated, approximate correction filters can be applied to the input data and the FK domain division may be greatly improved.

**Acknowledgements**

We would like to thank PGS for the permission to publish this work.

**References**


