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Digital Noise Attenuation of Particle Motion Data in a Multicomponent 4C Towed Streamer

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SUMMARY

A multicomponent (4C) towed streamer acquires both pressure and the full particle velocity vector with inline, crossline, and vertical components. In this paper, we present the characteristics of the noise recorded by the particle motion sensors in a multicomponent (4C) towed streamer that was tested in the North Sea. The particle motion sensors in a streamer exhibit streamer-borne noise such as longitudinal, transversal, and angular vibrations. The amplitudes of the vibrations are typically several orders of magnitude stronger than the corresponding noise recorded by hydrophones at frequencies below about 20 Hz. We introduce a multiscale noise attenuation algorithm that provides strong noise attenuation for particle velocity data at these frequencies. We show that a high-fidelity particle motion measurement can be obtained with this technique at frequencies down to 3 Hz. This enables 3D receiver deghosting and crossline reconstruction without making assumptions about the wavefield or the subsurface.
Introduction

Robertsson et al. (2008) introduced the concept of a multicomponent (4C) towed streamer that acquires both pressure and the full particle velocity vector with inline, crossline, and vertical components. Such a multicomponent streamer, for example, enables 3D receiver deghosting and crossline data reconstruction without making any assumptions about the wavefield or the subsurface (Özdemir et al. 2010; Özbek et al. 2010; Vassallo et al. 2010).

Recently, a multicomponent (4C) towed streamer that measures the full particle motion vector in addition to pressure was tested in the North Sea. The multicomponent streamer has a stiff construction and uses triaxial microelectromechanical systems (MEMS) accelerometers to record particle motion data (Figure 1). As the accelerometers are mounted in the stiff main body, they record streamer-borne noise such as longitudinal, transversal, and torsional vibrations. Figure 2 shows a typical FK spectrum of the recorded noise by transverse particle motion sensors. The dominant noise modes are torsional vibrations that start at the spatial Nyquist wavenumber and the transverse vibrations with dispersive frequency-wavenumber characteristics. The amplitudes of the vibrations are typically several orders of magnitude stronger than the noise measured by hydrophones at frequencies below about 20 Hz. Therefore, to be able to use particle motion data at the lower end of the seismic spectrum, powerful noise attenuation algorithms are required.

In this abstract, we present the characteristics of the noise recoded by the particle motion sensors in the multicomponent (4C) towed streamer and introduce the multiscale noise attenuation (MSNA) that we used to attenuate the noise. We show that a high-fidelity particle motion measurement is obtained at frequencies down to 3 Hz when the particle motion data acquired with the multicomponent streamer are processed with the MSNA techniques.

Particle motion noise in a multicomponent (4C) towed streamer

The multicomponent (4C) towed streamer uses three-axis MEMS sensors to measure the particle acceleration. When the sensors are orientated at an arbitrary angle \( \Theta \) in the y-z plane, the particle motion sensors will measure

\[
X = A_x + VN_x, \\
Y = A_y \cos \Theta - A_z \sin \Theta + g \sin \Theta + VN_y, + \alpha \tau + \alpha \xi, \\
Z = A_z \sin \Theta + A_y \cos \Theta - g \cos \Theta + VN_z + \beta \tau + \beta \xi,
\]

where \( A_x, A_y, \) and \( A_z \) denote particle acceleration; \( VN_x \) denotes longitudinal vibrations; \( VN_y \) and \( VN_z \) denote transverse vibrations; \( g \) denotes the gravitational acceleration; \( \alpha \) and \( \beta \) are scalar constants; \( \tau \) denotes angular acceleration; and \( \xi \) denotes centrifugal acceleration. The term corresponding to the centrifugal acceleration is much smaller than the other components of the acceleration. The gravity measurement and torsional noise measurement (that is related to angular acceleration) can be used to rotate the sensor to the cable coordinate system where \( x \) is inline, \( z \) points downwards, and \( y \) is the crossline direction.

Figure 1 The multicomponent (4C) towed streamer with triaxial accelerometers and hydrophone.

Figure 2 The FK spectrum of the vibration noise recorded by transverse particle motion sensors.
Multiscale noise attenuation

To attenuate the noise recorded by particle motion sensors, we use the multiscale noise attenuation algorithm that operates in the 2D discrete wavelet transform domain. The data acquired with nominal temporal and spatial sampling intervals have the finest scale, and the transformation of the data to coarser scales is achieved by using quadrature mirror filter (QMF) banks (Özbek, 2000). Each QMF splitting step in time and space decomposes the input data into low and high frequency and wavenumber data streams, respectively. The low-frequency (or wavenumber) data stream has double the sampling interval (or spacing) of the input data. This corresponds to a representation of the data at a coarser scale. The high-frequency (or wavenumber) data stream is saved for later QMF reconstruction. The QMF reconstruction step is the inverse of the QMF splitting step. Figure 3 shows cascaded application of QMF splits and reconstructions in time and space. If the filtering blocks are omitted, perfect reconstruction is achieved at the end of the analysis (downstream flow) and synthesis (upstream flow) steps.

As Figure 3 shows, the MSNA algorithm consists of two complementary algorithms: multiscale LACONA (MSL), and a multiscale dip filter (MSDF). The MSL is the adaptive part of the MSNA algorithm, and consists of QMF decompositions in time and space interlaced with an adaptive beamformer, which is chosen as LACONA (Özbek 2000) in this example. The adaptive algorithm used by MSL attenuates spatially localized, non-stationary noise. Due to the doubling of the sampling interval and spacing at each higher scale, the LACONA operator at larger scales has effectively larger aperture, i.e., higher resolution, while the size of the operator, i.e., the number of coefficients, does not change. Consequently, progressively sharper filters are applied at lower frequencies and wavenumbers, and stronger noise attenuation is achieved. The analysis and filtering steps are repeated until a desired level of scale is reached. After processing the signal at the coarsest scale, the processed signal components are merged iteratively to form lower scale signals.

The deterministic part of the MSNA algorithm is called the multiscale dip filter. It aims at removing the incoherent and stationary components of the noise. For efficient removal of noise without damaging the signal, the filter response is chosen to be sharper at lower frequencies where the signal is narrow band and the noise is stronger. Conversely, the filter response is shorter in space with a wider transition bandwidth in space at higher frequencies, where the noise is much weaker. The MSDF may use finite-impulse response (FIR) filters, infinite-impulse response filters, or a combination of both. When FIR filters are used, three TX filters at four different wavelet scales are used. Each filter is designed using the projection onto convex sets method (Çetin et al. 1997). Figure 4 shows typical frequency-wavenumber responses of filters designed using this method.

Figure 3 Multiscale noise attenuation flow that consists of multiscale LACONA and multiscale dip filter.

Figure 4 The FK responses of the three TX filters used by MSDF (first three plots) and the composite response (right)
The first plot shows the FK response of the filter used at the coarsest scale; the second plot shows the FK response of the filter used at intermediate scales; and the third plot shows the FK response of the filter used at the finest scale. The last plot shows the overall response of the MSDF. In this example, the passband and stopband specifications of the individual TX filters were chosen so that the coefficients of the effective MSDF gives a very good approximation to the ideal fan filter. 60-dB attenuation is achieved at 1150 m/s, and the -50-dB passband velocity is 1650 m/s.

Real data examples

Several field tests were conducted in the North Sea to test the performance of the multicomponent (4C) towed streamer and the noise attenuation flows. One of the experiments was conducted using six multicomponent streamers to acquire a small subset of a realistic 3D survey. The active length of each streamer was 500 m, and the cables were towed in parallel.

Figure 5 shows data acquired with the crossline component of the particle motion sensors in six multicomponent streamers. The scale of the TX plots is the same for each panel and no time-dependent gain was applied. A 3-Hz low-cut filter was applied to all panels. In this example, the cable depth was 22.5 m and the tow speed was 5 knots. Figure 5 shows that raw data with the 3-Hz low-cut filter is dominated by strong vibration and torsional noise, and the seismic signal is barely visible. Figure 5 shows the filtered shot records with the particle motion noise significantly attenuated. In this example, the amount of noise reduction is more than 30 dB at frequencies below 50 Hz.

Figure 6 shows sample data acquired with an 800-m long multicomponent streamer in the North Sea. In this example, the cable depth was 25 m and the tow speed was 5 knots. The TX displays show filtered pressure data, raw vertical component of the particle motion data, and the filtered vertical component of the particle motion data. Although the raw acceleration data are several orders of magnitude noisier than the raw hydrophone data, after noise attenuation, the amount of noise on the acceleration data was significantly reduced. Figure 6 also shows the power spectral densities of the filtered pressure and particle acceleration data as well as the upgoing wavefield computed from a signal and a noise window in a shot record. In this example, the upgoing wavefield was computed using the optimal deghosting algorithm (Özdemir and Özbek 2007).

Conclusions

We showed that the data measured with transverse particle motion sensors in a multicomponent (4C) towed streamer are dominated by strong transversal and torsional vibration noise at the lower end of the seismic spectrum. To be able to utilize particle motion data, we introduced the multiscale noise attenuation algorithm. We showed that the MSNA provides very powerful noise attenuation at
frequencies where the vibration noise is strongest. Consequently, data acquired with the multicomponent streamer and processed with the MSNA techniques provide valuable particle motion measurements at frequencies down to 3 Hz, enabling 3D deghosting and crossline reconstruction without making any assumptions about the wavefield or the subsurface.

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References


Figure 6 (top, left) filtered pressure data; (top, middle) raw and (top, right) filtered vertical component of the particle motion data; (bottom, left) signal from collocated pressure and particle motion sensor (bottom right) the spectra of signal (solid lines) and filtered noise (dashed lines).