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Signal Fidelity of Multicomponent (4C) Towed Streamer

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SUMMARY

A multicomponent (4C) towed streamer that measures not only scalar pressure wavefields, but also the three components of P-wave particle motion, was proposed by Robertsson et al. (2008). Because particle motion can easily be converted to a pressure gradient by using the equation of motion, such a streamer would enable acquisition of both pressure and the 3D gradient of pressure simultaneously.

To be able to put these proposed applications in practice, good fidelity of the 4C measurement is required.

We study the effects of the mechanical design of the streamer on the signal fidelity, review the sensor requirements, and present data examples from a 4C streamer demonstrating the possibility to record high signal fidelity with such a 4C towed streamer.
Introduction

A multicomponent (4C) towed streamer that measures not only scalar pressure wavefields, but also the three components of P-wave particle motion, was proposed by Robertsson et al. (2008). Because particle motion can easily be converted to a pressure gradient by using the equation of motion $\nabla P = -\rho \ddot{u}$, where $P$ represents pressure, $\rho$ represents density, and $\ddot{u}$ represents particle acceleration, such a streamer enables acquisition of both pressure and the 3D gradient of pressure simultaneously. Özbek et al. (2010) show how such measurements may be used to perform joint interpolation and deghosting of the pressure wavefield, while Vassallo et al. (2010) show how the seismic wavefield may be reconstructed at any point between streamers using both pressure and the crossline component of the pressure gradient.

To be able to put these proposed applications in practice, two main conditions must be met by particle motion recording in the streamer: fidelity of the measurement and a low enough noise level. In this abstract we cover the first aspect.

Theory

Norris et al. (2006) defined the signal fidelity for ocean-bottom cables (OBC) as “the precision of the reproduction of the true ground motion by the complete recording system”. This definition implies vector fidelity between the three components of particle motion. The definition can be adapted to towed-marine acquisition by replacing the true ground motion with true water motion. Hence, a multicomponent towed streamer should measure both the scalar pressure field by using hydrophones, and also the particle motion of the water associated with a propagating seismic wave.

We can assume that the pressure field is recorded with high fidelity by hydrophones. When densely spaced point-receiver hydrophone measurements are available along the streamer, we can also derive the inline pressure gradient (Eggenberger et al. 2011), as the waterborne acoustic signal is oversampled in the inline direction compared to the spatial Nyquist in the frequency band of interest.

To record transverse particle motion signal with high fidelity in a streamer, three conditions must be met: the sensor and sensor package must move in the same fashion as the surrounding water (equivalent to coupling at the seabed or the surface in land), the sensor must record faithfully this motion, and the orientation of the recorded motion must be known. Hence, we must study not only the sensor performance and its mounting, but also the mechanical construction of the streamer.

Streamer construction

A neutrally buoyant sensor, with dimensions much smaller than the seismic wavelength, will follow the motion of the surrounding water. To understand what happens when the sensor is mounted in a streamer, we modeled a neutrally buoyant streamer section surrounded by sea water. Realistic bending and extensional stiffness parameters were chosen. The source of excitation was chosen as a plane seismic wave arriving at a 45° incidence angle.

Figure 1 Particle motion response of streamer sections to 45° incidence plane waves (in the XZ plane): left Z response (vertical); right Z response for a section with a weight in the middle.
Figure 1 (left) shows that the streamer motion faithfully follows the surrounding water vertical motion associated with the seismic wave. Crossline (Y) response was not shown here as its response is similar to the vertical (Z) response.

To investigate the impact of density variation along the streamer, we modeled a streamer section with a weight in the middle of the streamer. The right plot in Figure 1 shows that the heavier part of the streamer does not record the full amplitude of the vertical motion signal and has a phase lag.

The effect of density variation along the cable can be reduced by bending stiffness. However, we must verify that the fidelity of the recorded signal is not compromised when the apparent wavelength is short along the cable. To test this, a finite element modeling (FEM) study was performed. A stiff streamer was modeled, and a step change in the pressure field along the streamer was introduced to evaluate the streamer’s ability to resolve a wavefield that has opposite polarities at different halves of the streamer.

Figure 2 (left) The stiff streamer model (cyan) and the excitation (red); (right) the streamer response.

Figure 2 shows that, even with this highly unrealistic excitation, the streamer accurately records the signal at offsets 1 to 2 m away from the step change in the polarity of the wavefield. Because this distance is much shorter than the smallest seismic wavelength that will be recorded in the seismic frequency band, we conclude that the streamer bending stiffness will not affect the fidelity of the signal recording.

Sensor requirements for good vector fidelity were proposed by Tessman et al. (2001), with a goal of recording true earth motion within $\pm 1\%$, implying vector fidelity of -40 dB. They state that the most challenging requirement on the sensor to achieve this goal is sensor orientation, as the accuracy must be better than 0.57°.

The orientation requirement becomes even more challenging in a dynamic environment (towed streamer, see Figure 3) compared to a static environment such as land or seabed. Figure 3 shows the fast variation of the orientation angle measured in a towed streamer over a duration of 40 s.

If not corrected for, the relatively large and fast streamer rotation will have two main effects: the signal will not be recorded in the correct orientation, and large amounts of noise will be generated due to varying gravity projection. The second effect will be predominant, particularly on the crossline component.

Figure 3 The measured rotation of a towed streamer under as a function of time.
Therefore, it is essential to measure and correct for streamer rotation with a high resolution in time. A good sensor should then be lightweight and able to record and correct for its tilt at a very high rate. A MEMS geophone is a good candidate and gimbal mechanisms are best avoided.

Examples

Based on these learnings, a multicomponent streamer using MEMS geophones was designed and data acquired. To verify the fidelity of the particle motion recording on a seismic arrival, we compared the particle velocity in the direction of propagation of the seismic wave and the pressure recording. They should be proportional with proportionality factor equal to the acoustic impedance of the water.

![Figure 4](image)

**Figure 4** Near-vertical seabed reflection recorded on collocated geophones and hydrophones in a multicomponent streamer and their sum. From left to right: pressure (blue), velocity scaled by acoustic impedance (red), and weighted sum (green) for one sensor pair, ten consecutive pressure traces, vertical velocity traces, and PZ sum.

Figure 4 shows a very good match in amplitude and phase between scaled vertical velocity and pressure for the upgoing arrival (8.1 s to 8.13 s, left). This result is consistent on all traces, as shown by the results of the PZ sum on 10 consecutive sensor pairs, where the sea-surface ghost arrival is systematically removed.

We also checked the vector fidelity by computing the linearity of the Y and Z data on first arrivals. The left plot in Figure 5 shows the hodograms of 64 sensor pairs along the streamer for the direct arrival and the linearity computed as one minus square of the correlation coefficient. The right plot in Figure 5 shows excellent linearity achieved on all sensor pairs.

![Figure 5](image)

**Figure 5** (left) YZ hodograms of 64 sensor pairs along a streamer for the first arrival from a source fired to the side and below the streamer; (right) YZ linearity of these arrivals.

The excellent vector fidelity is also illustrated by the capacity to correctly determine the azimuth of seismic arrivals from polarization analysis. Another seismic survey was conducted in close proximity (approximately 25 km away), which caused visible seismic interference, and the position of the vessel was known from Automatic Identification System (AIS), allowing for a comparison between the measured azimuth from the seismic interference data and the analytical azimuth based on sensor and interference source positions. The interference came from a direction almost orthogonal to the multicomponent streamers, with an azimuth between 80° and 90° with respect to positive inline of our spread. In Figure 6, we show a comparison between the analytical azimuth and the measured signal.
azimuth. Because the arrival time of the interference changes from shot to shot (see top panel), we searched for coherent signal with azimuths different from the azimuthal range consistent with our own source and receiver geometry and calculated trace-by-trace the median azimuth of such coherent but out-of-plane events. The comparison between the measured and analytical interference azimuths holds very well (bottom panel) for this far-offset event and shows that out-of-plane seismic interference can be detected and its azimuth correctly determined.

**Figure 6** Polarization-based azimuth estimate for several adjacent shots (top panel). Azimuth is measured in degrees relative to positive inline. Bottom panel: comparison between the measured azimuth and the analytical azimuth obtained from known vessel positions.

**Conclusion**

We showed that high signal fidelity can be recorded in a 4C streamer.

Good signal fidelity requires careful streamer construction and selection of mechanical parameters, high-fidelity particle motion sensors, and faithful recording and correction of the sensor orientation.

**References**


