Z013

Characterization of Noise Modes in Multicomponent (4C) Towed-streamer

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SUMMARY

The design of a seismic streamer must balance between optimizing for acoustic performance, robustness and handling requirements. The mechanical properties of a streamer will strongly impact the acoustic performance by shaping the noise modes experienced by the streamer and the filterability of the noise as measured by the sensors in the streamer. Development of a multicomponent streamer requires extensive analytical and numerical modelling to optimize the acoustic performance. In this abstract, we present the use of three-axis accelerometers, which has allowed detailed understanding of the in-situ motions of the cable, and enabled the development of a multicomponent streamer platform.
Introduction

Marine seismic acquisition is subject to many different sources of noise and sensor perturbations that degrade the fidelity of the acquired pressure signal and reduce the efficiency of seismic acquisition (Fulton, 1985; Smith, 1999). For instance, due to constant excitation from water flowing around it, the cable is subject to several modes of vibrations. Unlike hydrophones that could be made insensitive to vibrations by design, the particle motion sensors are directly sensitive to cable self-vibration. Therefore, the development of multicomponent streamers that measure particle velocity is more challenging than design of conventional streamers that measure only pressure.

The characteristics of the strongest noise modes picked by particle motion sensors depend on the mechanical properties of the seismic streamer. These noise modes can be shaped to enable effective noise attenuation. However to achieve this, the noise modes in the streamer must be carefully studied through analytical and numerical modelling.

Recently, a multicomponent streamer that measures the full particle motion vector in addition to pressure was developed and tested in the North Sea. This multicomponent streamer has a stiff construction and uses triaxial accelerometers to measure particle motion data (Figure 1). As the accelerometers are mounted in the stiff main body, they measure streamer-borne noise such as longitudinal, transversal, and torsional vibrations.

In this abstract, we present the analytical characterization of dominant noise modes to which particle motion sensors are sensitive.

Transverse vibrations

The frequency-wavenumber dispersion relationship of a stiff streamer can be approximated by the transverse (flexural) vibration of a slender uniform beam subject to axial tension. The equation of motion for the transverse displacement $\psi(t, x)$ of the beam is defined by a fourth-order partial differential equation (PDE) with constant coefficients (Tongue, 2002; De Silva 2007)

$$EI \frac{\partial^4 \psi(x,t)}{\partial x^4} - T \frac{\partial^2 \psi(x,t)}{\partial x^2} + m \frac{\partial^2 \psi(x,t)}{\partial t^2} = h(x,t)$$

(1)

where $t$ is time, $x$ is the coordinate of the inline axis, $E$ is the Young’s modulus, $I$ is the area moment of inertia, $T$ is the axial tension, $m$ is the mass per unit length, and $h(x,t)$ is the external force per unit length. For a stationary and neutrally buoyant streamer, the mass per unit length is given by $m = \pi d^2 \rho / 4$, where $\rho$ is the density of sea water and $d$ is the outer diameter. When the streamer is towed in the fluid medium, the density $\rho$ is replaced with $\rho_a$ to account for the added mass effect as the towed streamer moves some volume of fluid with it.

Figure 2 shows the frequency-wavenumber spectrum of synthetically generated transversal vibration noise according to equation (1). The vibration noise energy is localized around a frequency-wavenumber dispersion curve (Selvadurai, 2000; De Silva 2007). The eigen-functions of the homogenous PDE corresponding to the PDE in equation (1) give the resonance frequencies and wavenumbers, i.e., the frequencies and wavenumbers at which the vibration noise has its peak amplitudes. It can be shown that the eigen-functions have the following form:

$$g(x,t) = \exp(j2\pi(f t + kx))$$

where $k$ is the wavenumber and $f$ is the frequency, and the corresponding characteristic equation of the homogeneous PDE is
The corresponding phase velocity can be obtained as a function of resonance frequencies and wavenumbers:

\[ v_p(k) = \frac{f(k)}{k} = \frac{2}{d} \sqrt{\frac{4\pi^2 k^4 EI + T}{\pi \rho_u}} \]  

(3)

For a fluid-filled or gel streamer, the Young’s modulus can be taken as zero; therefore, the frequency-wavenumber dispersion relation given in (2) reduces to

\[ \frac{k^2}{f^2} T - \frac{\pi d^2 \rho_u}{4} = 0 \]  

(4)

The corresponding phase velocity is given by

\[ v_p(k) \equiv \frac{f(k)}{k} = \frac{2}{d} \sqrt{\frac{T}{\pi \rho_u}} \]  

(5)

which does not change with frequency.

The velocity of the transversal vibration noise is typically slower than the seismic signal and ranges around 30 to 120 m/s in a stiff cable. Figure 3 shows the frequency-wavenumber dispersion relationship for a gel (blue) and a stiff section (green) together with the signal cone (black) in an FK plot. The figure illustrates how increased transversal propagation speed, due to bending stiffness in a stiff section, can prevent aliasing into the signal cone.
Longitudinal vibrations

Mathematically, the equation governing the longitudinal vibrations of a streamer simplified to a uniform beam is a second-order PDE with constant coefficients (Tongue, 2002; De Silva 2007):

\[ EA \frac{\partial^2 \phi(x,t)}{\partial x^2} - m \phi(x,t) = q(x,t) \]  

(6)

where \( \phi(x,t) \) is the longitudinal displacement, \( E \) is the Young’s modulus, \( A \) is cross-sectional area, \( m \) is mass per unit length, and \( q(x,t) \) is the forcing term. The characteristic equation for the homogeneous differential equation gives the phase velocity of the longitudinal vibration noise as:

\[ f / k = \frac{EA}{m} \]  

(7)

For a typical streamer with Kevlar stress members, the inline vibration noise propagates at a velocity close to 1500 m/s.

Angular (torsional) vibrations

The particle motion sensors are subject to rotation about the longitudinal axis as the streamer is being towed and, as a result, the measurement acquired by the particle motion sensor contains noise that is attributable to this rotation. The rotational propagation velocity for a streamer simplified as a beam with a uniform cross section depends on shear stiffness and density, and is governed by the following differential equation (Tongue, 2002; De Silva 2007)

\[ G \frac{\partial^2 \Theta(t,x)}{\partial x^2} - \rho \Theta(t,x) = 0 \]  

(8)

where \( \Theta(t,x) \) is the angular displacement, \( G \) is the shear modulus of elasticity and \( \rho \) is the density. The velocities will be practically zero for a fluid-filled or gel-filled streamer and around 500 to 1000 m/s for a stiff section. Torsional vibration could potentially leak onto transversal sensors if they are offset from the centerline of the streamer. Hence, the streamer platform should be carefully designed to avoid such leakage.
Particle motion sensors measure changes in acceleration including the gravitational acceleration. When the cable is properly balanced, the gravitational acceleration will be measured by only the transverse components of the sensors:

\[
Y(t, x) = g \sin \Theta(t, x) \\
Z(t, x) = -g \cos \Theta(t, x)
\]  

(9)

In this equation, \( \Theta(t, x) \) is the orientation of the \( x \)-th sensor at time \( t \). Figure 5 shows the amplitudes of this equation in m/s\(^2\) plotted for angles between \([-\pi/2, \pi/2]\).

If the orientation of the sensors is not corrected accurately, the \( y \)-component of the particle motion sensor will be subject to static gravitational acceleration noise:

\[
Y_r(t, x) = g \sin \Theta(t, x) \equiv g \Theta(t, x) \\
Z_r(t, x) = -g \cos \Theta(t, x) \equiv -g
\]

(10)

where \( \Theta(t, x) \) is the residual uncorrected portion of the orientation angle.

Conclusions

Careful selection of streamer properties can shape the vibration noise to maximize the effect of digital filtering of particle motion sensors in a seismic streamer. By analytical and numerical modelling, the governing vibration modes of a seismic streamer were investigated in detail, which has enabled optimization of acoustic performance under the constraints of robustness and handling requirements.

References


