Solid streamer noise reduction principles

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Summary

Today's solid streamers are generally less sensitive to mechanical noise originating from sea swell effects and are insensitive to vibration from depth controllers (birds) and mechanical towing equipment. In addition, for a given level of sea swell, they can be towed shallower without a significant noise increase.

The dominant transport mechanism for parasitic or unwanted vibration in any streamer design (whether using solid or fluid-based buoyancy) is the axial extensional wave.   If such extensional waves are permitted to generate significant pressure or stress at the locations of the hydrophone elements, then undesirable coherent noise will result.

In fluid streamers, coupling between extensional waves and hydrophones occurs through the medium of bulge waves. With extremely careful mechanical design, and by forming linear arrays of individual hydrophone elements which exploit the low speed of bulge waves, fluid filled streamers may achieve acceptable mechanical noise performance. Single hydrophones in fluid streamers are always excessively noisy.

In a solid buoyancy streamer the low speed bulge waves are replaced by higher speed compressional waves, thus precluding array forming as a primary means of mechanical noise reduction within the critical 3Hz to 50Hz band.

However with appropriate design and materials, a high degree of noise isolation can be realised. As mechanical isolation must be achieved independently of the use of arrays, both arrays and single hydrophones in a solid streamer can be relatively quiet.

One successful method of manufacturing a solid streamer encloses the hydrophone element in a relatively stiff package which resists the stress and strain normally induced by the passage of axial extensional waves. This package or Strain Isolation Module (SIM) contains acoustically transparent coupling fluid and also includes an elongated external diaphragm or diaphragms providing a high degree of turbulent noise reduction.

Using this technology, improvements in mechanical noise isolation of the order of 15dB have been measured at sea. Observed improvements in field results are well predicted by simple axial wave theory.

Introduction

Marine geophysical streamers are a popular data acquisition solution principally because they produce high quality data on a large scale at low cost. The last 20 years has seen continuous improvement in streamer technology – greater reliability has been accompanied by improved data quality and reduced cost of ownership.

Continuous movement at 5 knots presents a unique set of acoustic challenges.   All seismic streamers are subject to significant mechanically-induced noise, turbulent flow noise, and acoustic noise. Other sources, such as pre-amplifier thermal noise, are minor by comparison.   Of the above three dominant sources, mechanically induced noise is responsible for the majority of decisions to halt commercial data acquisition on grounds of degraded streamer data quality.

One of the more important advances in technology has been the solid streamer, which is more robust than the older fluid-filled construction. In a solid streamer the buoyancy fluid is replaced by buoyant flexible polymer, usually either polyethylene or polyurethane based (see Fig 1.)

It is well known that solid streamers are generally less sensitive to mechanical noise originating from sea swell effects, can be towed shallower without a significant noise increase, and are insensitive to vibration from depth controllers (birds) and mechanical towing equipment.
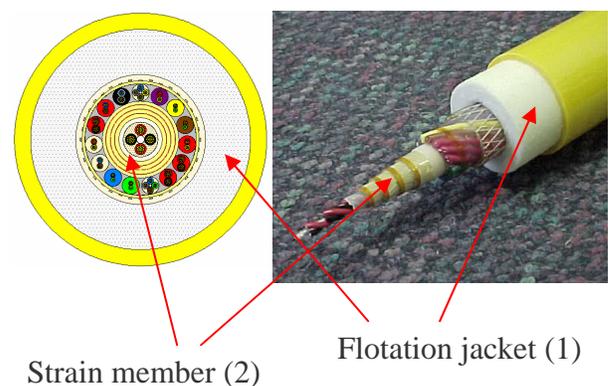

Flotation jacket (1)

Strain member (2)

Fig. 1. Solid streamer construction showing solid, flexible buoyancy material replacing fluid buoyancy.

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In order to impact on seismic streamer signal to noise ratio, mechanical noise must be:

     i)   generated
     ii)   transported and
     iii)   coupled

to the sensing elements. Mechanical energy originates from sea swell (for example cross flow), vessel tugging, and cable attachments (for example depth controllers). In practice, all three sources rise in amplitude markedly with any deterioration in weather conditions.

In the following discussion we describe and anlyse the transport and coupling aspects of streamer noise control and then draw some conclusions regarding best practice in solid streamer design. In this, a comparison between older and new designs is pertinent, and cable design concepts are simplified in the interest of clarity.

The dominant transport mechanism for parasitic or unwanted vibration in any streamer design (whether using solid or fluid-based buoyancy) is the axial extensional wave, which travels along the strength members at a high speed dependant on the number and stiffness of the strength members and the mass loading applied by the streamer body. Observed speeds are in the region of 1200 to 1600 metres per second, and energy dissipates over a few 10's of wavelengths. This axial pathway carries no useful seismic signal energy.

Fluid Filled Streamers and Arrays

In fluid streamers, coupling between unwanted extensional waves and hydrophones occurs through the medium of bulge waves (see Fig. 2).
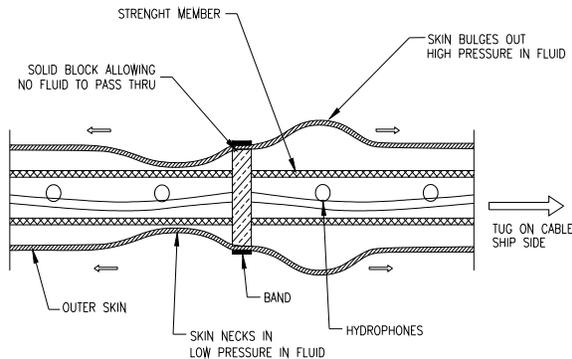

Fig. 2. Bulge wave generated at an oil blockage within a fluid-filled streamer

Bulge waves travel at approximately 30 to 40 metres per second away from any oil blockage attached to the strength members. These slower waves largely dissipate over 10 or so wavelengths

from their point of generation, but at the lowest seismic frequencies of practical interest (eg 3Hz) this could be at least 100 metres. As shown in figure 2. bulge waves tend to be generated in pairs with opposite polarity, which provides a clever and practical means to reduce their impact on hydrophone signals (Giles and Steetle, 1989).

With extremely careful design, fluid filled streamers *may* achieve acceptable mechanical noise performance only when:

     i)   hydrophones are precisely placed so that bulge waves of equal amplitude but opposite polarity cancel at the hydrophone location, and
     ii)   the relatively low speed of bulge waves (30 to 40 metres per second) is exploited by forming arrays of a number of discrete hydrophones.

A hydrophone array realises a low pass frequency filter in the in-line direction, with cut-off frequency given approximately by:

$$F_{CUT} \approx C_V / L_H \qquad (1)$$

where C_V is the inline wave speed, and L_H is the hydrophone array (or group) length. Thus the cut-off frequency for a 12 metre group responding to a bulge wave at 35 metres per second is approximately 3 Hz. Above 3Hz the energy is attenuated by approximately 15 dB, and below 3Hz the attenuation falls to zero. It is immediately obvious that noise minimisation requires low C_V and high L_H. It is also clear that single hydrophones in fluid streamers experience 15dB more mechanical noise due to un-attenuated bulge waves.

Excessively long arrays are undesirable as they may impact on the higher frequency seismic signals, containing steeply dipping or wide offset signal energy. Bulge wave speed and damping must be carefully controlled by precise selection of the grade of external jacket polymer, with the more robust grades unfortunately tending to raise C_V. In practice, fluid cable designs seldom reach a satisfactory compromise between mechanical robustness and acceptable mechanical noise across the full seismic bandwidth, and in addition performance often degrades with any wear and tear over the product's service life.

A full discussion on designing a quiet fluid streamer, including consideration of turbulent flow noise, is a complex topic and goes beyond the scope of this paper.

Solid Streamers and Arrays

Attributing the noise reductions of solid streamer technology to the absence of "bulge waves" only goes part of the way to explaining the improvement. In a solid buoyancy streamer the low speed bulge waves are replaced by higher speed compressional waves. In practice, the speed of mechanical waves in solid buoyant material can range from 300 metres per second to 1800 metres per second, depending on the intrinsic

elastic modulus and the intimacy of the coupling between the flexible buoyancy and the stiff strength members (see Fig. 1). The resulting array cut-off frequency range (assuming a 12 metre group length) is 25 Hz to 150 Hz for axial compressional waves. This and the dominance of mechanical noise energy below 20Hz precludes array forming as a primary means of noise reduction in solid streamers, although it can be useful in other regards as noted later in this paper.

At low frequencies the axial vibration induced pressure $P_X(f)$ within the solid, flexible buoyancy material is a function of dynamic axial strain. $P_X(f)$ is given approximately by:

$$P_X(f) \approx \rho_C \cdot C_V \cdot k_B \cdot \ddot{U}_X(f) / 2\pi f \qquad (2)$$

where ρ_C is the cable density, C_V is the axial extensional wave speed, $\ddot{U}_X(f)$ is the axial cable acceleration as a function of frequency, and k_B is the ratio of stiffness between the buoyancy material and the cable as a whole including strength member (typically around 0.01 to 0.02). Calculations based on this formula and known towing vibration levels predict induced dynamic pressure within the buoyant material of around 100 to 200 μbars RMS (6Hz to 200Hz) making it impractical to directly mount hydrophone elements within the buoyant material.

Hydrophone mechanical noise isolation

Starting from equation (2) one way to control mechanical noise is to choose flotation material with extremely low $\rho_C C_V$ (mechanical impedance) but materials in this class turn out to be extremely soft and lacking durability under mechanical impact or streamer recovery. A preferable solution is to incorporate a specific individual transducer packaging solution, with the attributes of:

> - maximum isolation from dynamic stress in the flotation material
> - minimum signal amplitude loss and phase distortion
> - robustness with good mechanical impact protection.
> - attenuation of turbulent flow noise

US patents No. 5,600,608 (1997) and No. 6,853,604 B2 (2005) describe streamer hydrophone packages which reduce mechanical noise coupling in the fashion described above (see Fig. 3). The former concept incorporates acoustically transparent coupling fluid within the space (25) and also includes an elongated external diaphragm to provide a high degree of turbulent noise reduction. A further patent application describes a flexible version of this carrier.

The hydrophone carrier, or Strain Isolation Module (SIM), provides around 40dB or better isolation from the stress in the buoyancy attached either side of the carrier. This is achieved by creating a relatively large stiffness contrast between the carrier and buoyancy, further lowering the factor k_B in equation (2).
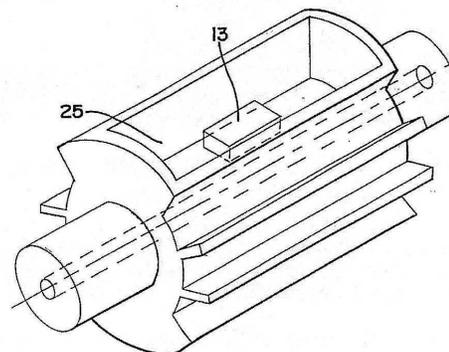

Fig. 3. Hydrophone carrier defining a zone (25) for hydrophone element (13) which is free from noise induced by axial mechanical waves.

Thus the levels of vibration-induced noise sensitivity are better than 40dB lower than equation (3) would predict. In average towing conditions the resulting mechanical noise component integrated over the 6Hz to 200Hz band is measured at less than 2 μbars RMS rising to 4 to 5μbars RMS in moderate seas. As mechanical isolation is achieved independently of the use of groups, both groups and single hydrophones remain relatively quiet even as the weather deteriorates.

Flow noise and transverse waves

Arrays are still useful in solid sytreamers. The package in fig. 3 effectively attenuates turbulent flow noise (TBL) due to it's elongated integration surface. Typical single-phone measurements at 5 knots for a 20cm diaphragm length indicate 5 μbars RMS (6Hz to 200Hz) with a broad spectrum. As there is very little TBL correlation phone-to-phone in a seismic group, total flow noise is given by:

$$P_{AT}(f) \approx P_{HT}(f) \cdot (N_H)^{-1/2} \qquad (3)$$

Where $P_{AT}(f)$ is the group flow noise, $P_{HT}(f)$ is the single phone flow noise and N_H is the number of phones per group. With $N_H = 8$ this gives less than 2 μbars RMS un-correlated flow noise, that is, a useful reduction.

Transverse waves, present in all towed cables, are excited primarily by sea swell action. The wave speed is given by:

$$C_T = \sqrt{(F_T / M_S)} \qquad (4)$$

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where F_T is the cable tension and M_S is the mass per unit length of the cable. C_T typically ranges from 20 to 40 metres per second (ie similar to bulge wave speeds), so that standard seismic groups still provide useful reduction ($\approx$ 15dB) in transverse cable noise. Interestingly, the primary mode of coupling is via the changing pressure head above the hydrophones, giving the following coupling equation:

$$P_Z\,(f) = \rho_w \cdot g \cdot \ddot{U}_Z(f) \,/\, 4\pi^2 f^2 \qquad (5)$$

where ρ_w is the water density, g is the gravitational constant and $\ddot{U}_Z(f)$ is the tranverse cable acceleration as a function of frequency. Due to damping and the factor $1/f^2$ the bandwidth of this mode is greatly reduced (typically $\leq$ 6Hz) and therefore the hydrophone spacing can be greater on Nyquist sampling grounds, resulting in a halving of the number of hydrophones per channel (8 per group vs 16) compared to fluid filled streamers.

Field Results

Fig. 4. is a typical field noise record collected from a hybrid streamer consisting of 1,350 metres of Sercel Solid Streamer ahead of 4000 metres of fluid streamer. This streamer implemented a hydrophone carrier concept similar to that shown in Fig 3. During this test the seas were moderate.
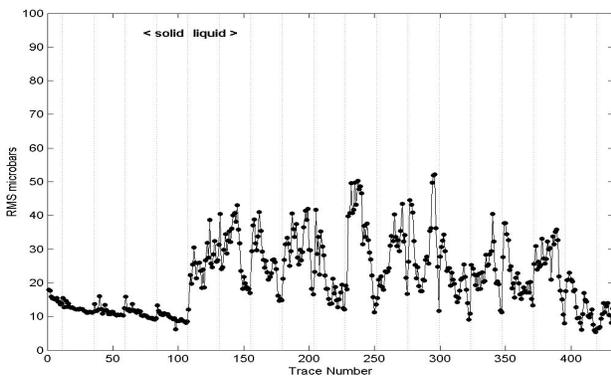

Fig. 4. Noise comparison between Sercel Solid Streamer and fluid filled streamer (moderate seas).

The majority of the noise in the solid sections consisted of flow noise and acoustic background noise, and results overall are consistent with the predicted vibration-induced component of about 5 μbars RMS. The noise in the fluid sections is predominantly mechanical and is around 15dB above the mechanical noise in the solid sections.

Conclusions

With extremely careful mechanical design, and by forming linear arrays of individual hydrophone elements which exploit the low speed of bulge waves, fluid filled streamers may achieve acceptable mechanical noise performance over a limited bandwidth, however single hydrophones will always be unacceptably noisy.

Today's solid streamers are generally less sensitive to mechanical noise originating from sea swell effects and are insensitive to vibration from depth controllers (birds) and mechanical towing equipment.
In a solid buoyancy streamer the low speed bulge waves are replaced by higher speed compressional waves. Due to this higher wave speed, array forming cannot be a primary means of mechanical noise reduction in solid streamers.

One successful method of manufacturing a solid streamer encloses the hydrophone element in a relatively stiff package which resists the stress and strain normally induced by axial extensional waves. Using this technology, improvements in mechanical noise isolation of the order of 15dB have been measured relative to fluid filled streamer performance.

Solid streamers designed in this way can extend the available data acquisition time, whilst providing generally improved signal to noise ratio.

Acknowledgements

References

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