A Marine Seismic Source with Enhanced Low and Reduced High Frequency Content

G. Baeten[1], D. Chavan[1], B. Kuvshinov[1], F. Ten Kroode[1]*, S. Ronen[2], S. Chelminski[2], J. Chelminski[2]

[1] Shell International E&P BV; [2] Low Impact Seismic Sources

Summary

We describe the physical principles underlying a new type of marine seismic source, the so-called Tuned Pulse Source and show that it generates more low frequency and less spurious high frequency content than conventional airgun arrays. The enhanced low frequency content is attractive for seismic exploration. The reduced high frequency content leads to a lower environmental impact. We show measurements on a prototype of such a source and model its relevance for Full Waveform Inversion.

Introduction

It is well known that low frequencies are very beneficial for seismic exploration. The reasons for this are manifold. First, low frequencies scatter less in the subsurface, which leads to deeper penetration into the earth. This is obviously relevant for current exploration efforts, which tend to go for ever deeper hydrocarbon accumulations, oftentimes under hard and/or rugose contrasts, such as salt and basalt. Second, a richer low frequency content leads to a better peak-to-side lobe ratio of the seismic wavelet, which somewhat counter intuitively translates into higher resolution. It would also mitigate or eliminate the need to build so-called low frequency models in quantitative interpretation. Finally, it would mitigate the well-known cycle skipping problem in Full Waveform Inversion. We refer to ten Kroode et al. (2013) for several examples illustrating these points.

Generating a seismic signal with good S/N and stable phase in the 1-4 Hz band is a hard problem both in onshore and offshore situations. This abstract pertains to the marine problem and more in particular to pneumatic marine sources. Sources are often divided into two groups: impulsive and non-impulsive (oscillatory) ones. Conventional airguns can be viewed as hybrid-type sources. The impulsive part of the seismic signal is generated during the initial air release into the water through the airgun ports. The released air also forms bubbles and the oscillations of these bubbles generate the non-impulsive part of the seismic signal. The low frequency signal of airguns is coming from the non-impulsive part. Until about a decade ago, low frequency content and reduced environmental impact were not high priorities. Airguns were designed to have short rise times. Airgun arrays were designed to maximize the initial seismic pulse and to minimize the effect of subsequent bubble oscillations. Airgun arrays are therefore essentially impulsive sources. The reason for this design is that it leads to an easy designature procedure. It does however reduce the low frequency output of the array (Hegna and Parkes 2011). In contrast, a Tuned Pulse Source (Ronen and Chelminski 2017) radiates the major part of the seismic energy through bubble oscillations. Also, the TPS is designed to have a long rise time and a lower sound pressure level than airguns. Most of the acoustic energy emitted by TPS is non-impulsive. It reduces its environmental impact.

Theory – the physics of bubble oscillations

Rigorous analysis of bubble oscillations based on hydrodynamic equations is rather complicated, even in the case of a spherically symmetric bubble (Plesset and Prosperetti 1977). An example of such an analysis can be found in the paper by Ziolkowski (1970). Below we analyse bubble dynamics from first principles, using semiqualitative arguments.

We consider a spherical bubble of radius R, whose boundary moves with velocity $U_R = dR/dt$. The motion of the bubble induces motion of water everywhere outside the bubble. This induced water motion is almost incompressible. The water flux through each spherical surface is the same, which implies that the radial water velocity U_w varies with the distance r from the bubble centre as $U_w = U_R R^2/r^2$. The kinetic energy of the water in the annulus between surfaces with radii r and $r + dr$ is equal to $2\pi r^2 \rho U_w^2 dr$, where ρ is the water density. Integrating this expression from R to infinity, we find that the total kinetic energy of the moving water is equal to $E_w = 2\pi R^3 \rho U_R^2$. The radial momentum of the moving water is obtained by differentiating E_w with respect to U_R (by analogy with standard relations in classical mechanics $E = mv^2/2$ and $J = mv = dE/dv$) and it is equal to

$$J_w = 4\pi R^3 \rho U_R. \qquad (1)$$

One can also obtain equation (1) by assuming that most of contribution to the water radial momentum comes from the annulus with the width of about R near the bubble boundary. The water velocity in this annulus is taken to be U_R and the water motion outside the annulus is neglected.

The bubble motion in the radial direction is governed by Newton's second law $dJ_w/dt = F$, where F is the force acting on the bubble in the radial direction. The radial force is created by the difference between the bubble pressure p_b and the ambient (hydrostatic) pressure p_w and it is equal to $F = 4\pi\, R^2\, (p_b - p_w)$. Substituting here equation (1) we obtain the Rayleigh equation,

$$\frac{\rho}{R^2}\,\frac{d(\,R^3\,U_R)}{d\,t} = p_b - p_w\,. \tag{2}$$

The conventional Rayleigh-Plesset equation differs from equation (2) by terms describing water viscosity and energy losses due to sound emission.

The bubble spends most of the time in the expanded state, where its pressure p_b is much smaller than the pressure p_w of ambient water. In this state, the radial bubble velocity and the pressure in the bubble are small. Neglecting the terms with p_b and dR/dt in equation (2) we reduce it to $(\rho/2)\ d^2\,R^2/dt^2 = -p_w$. Solving this equation, we find that the bubble radius, R, is approximately equal to

$$R^2 = R_{max}^2 - (p_w/\rho)\ t^2, \tag{3}$$

where t is the time starting when the bubble is at its maximal radius R_{max}. It takes time $R_{max}\ (\rho/p_w)^{1/2}$ for the bubble to collapse from its maximally expanded state to a state with a relatively small radius. The period of bubble oscillations T is approximately twice this collapse time,

$$T = 2R_{max}\ (\rho/p_w)^{1/2}. \tag{4}$$

When an initially small, high-pressure air bubble expands to its maximum volume $V_{max} = (4\,\pi/3)R_{max}^3$, its initial energy E_0 is converted into work $A = p_w\,V_{max}$ against the ambient water pressure. The initial bubble energy E_0 is approximately equal to the thermal energy of air contained inside the airgun, $E_0 = p_0\,V_0/(\,\gamma - 1)$. Here, p_0 and V_0 are the pressure and volume of the airgun, and $\gamma = 1.4$ is the adiabatic constant of air. From the condition $E_0 = A$ it follows

$$R_{max} = 0.84\ (p_0/p_w\,)^{1/3}\ V_0{}^{1/3}. \tag{5}$$

Combining equations (4) and (5) we get the Rayleigh-Willis formula,

$$T = \text{k}\ \rho^{1/2} p_0{}^{1/3}\ V_0{}^{1/3}/p_w{}^{5/6}. \tag{6}$$

Here, k is a numerical constant, which according to the above estimations is equal to 1.7. This constant can be somewhat lower or higher depending on the details of bubble dynamics, which are not considered here.

The pressure of ambient water p_w is equal to $p_a + \rho g h$, where p_a is the atmospheric pressure, g is the gravitational acceleration and h is the bubble depth. Since $p_w > p_a$, the period of bubble oscillations T satisfies the condition $T < 2\,R_{max}\ (\rho/p_a)^{1/2} \simeq R_{max}/5$. Here, T is measured in seconds and R is measured in meters. Eigen frequencies of about 1 Hz ($T \simeq 1$ second) can be achieved only with unrealistically large bubbles, $R_{max} > 5$ meters. On the other hand, generation of bubbles with $R_{max} \simeq 2 - 3$ meters and $T \simeq 0.5$ second seems feasible. Equation (5) shows that such air-bubbles can be generated at shallow depths by an airgun with pressure $p_0 \simeq 10^3$ psi and volume $V_0 \simeq 10^5$ cubic inches.

Measurements on a Tuned Pulse Source

In 2018, a series of measurements were made using a Tuned Pulse Source in a quarry in the US. Several TPS volumes ranging from 600 cui to 4800 cui were used. The firing pressure for the different experiments was varied with the maximum pressure reaching 1000 psi. Standard airguns were fired to provide reference data for comparison purposes. Near field hydrophones were installed to record the emitted pressure wave, in the immediate vicinity of the airguns to minimize the impact of side- and bottom reflections from the quarry.

The test objectives were the assessment of mechanical integrity of the TPS, the evaluation of the geophysical properties of the emitted wavefield, and the acquisition of calibration points for the modeling program that is being developed. The assessment of the mechanical integrity included the evaluation of dedicated pressure and temperature measurements that were made inside the TPS (Figure 2). The geophysical analysis focused on an assessment of shot repeatability and spectral properties including low frequency amplitudes and reduced high-frequency content for environmental protection. Measurements with different TPS volumes are shown in Figure 3a. A comparison between a TPS and a conventional airgun with the same energy (Figure 3b) demonstrates the reduced high-frequency content of the TPS source, due to the reduced firing pressure and the improved mechanical design aimed at reducing cavitation and increasing the rise time of the initial pulse. Good shot-to-shot repeatability is shown in Figure 3c for a 2400 cui TPS source. Comparisons with modeling software show excellent agreement between simulation and measurement within the seismic bandwidth for a large range of airgun volumes and firing pressures, with differences occurring primarily for frequencies above 100 Hz - a common limitation for most airgun modeling packages. An example of the excellent correspondence between model result and measurements is shown in Figure 3d. This, and other results that were obtained, provide confidence that accurate modeling results for the low frequency part of the generated wavefield can be obtained.

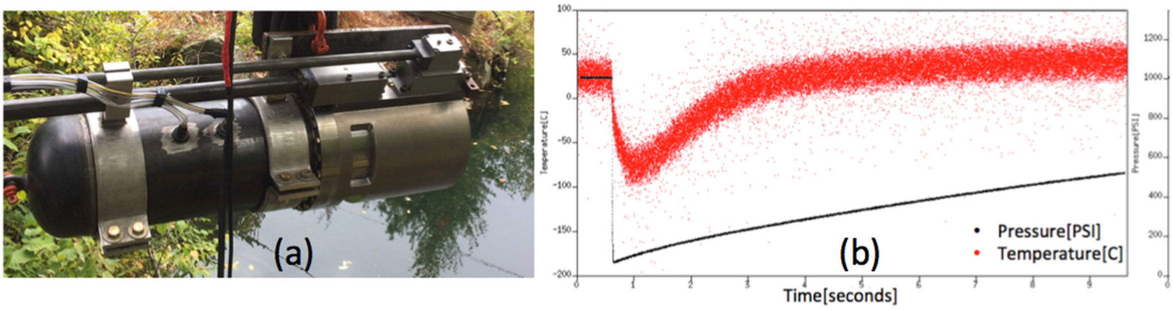

Figure 2 *(a) TPS instrumented with pressure and temperature sensors. (b) Pressure and temperature measured inside the firing chamber of a TPS. The initial pressure of 1000 psi drops to 70 psi. A slow responding temperature sensor indicated that an initial temperature of 20º C drops to -75º C. The firing chamber is connected to a supply of compressed air.*

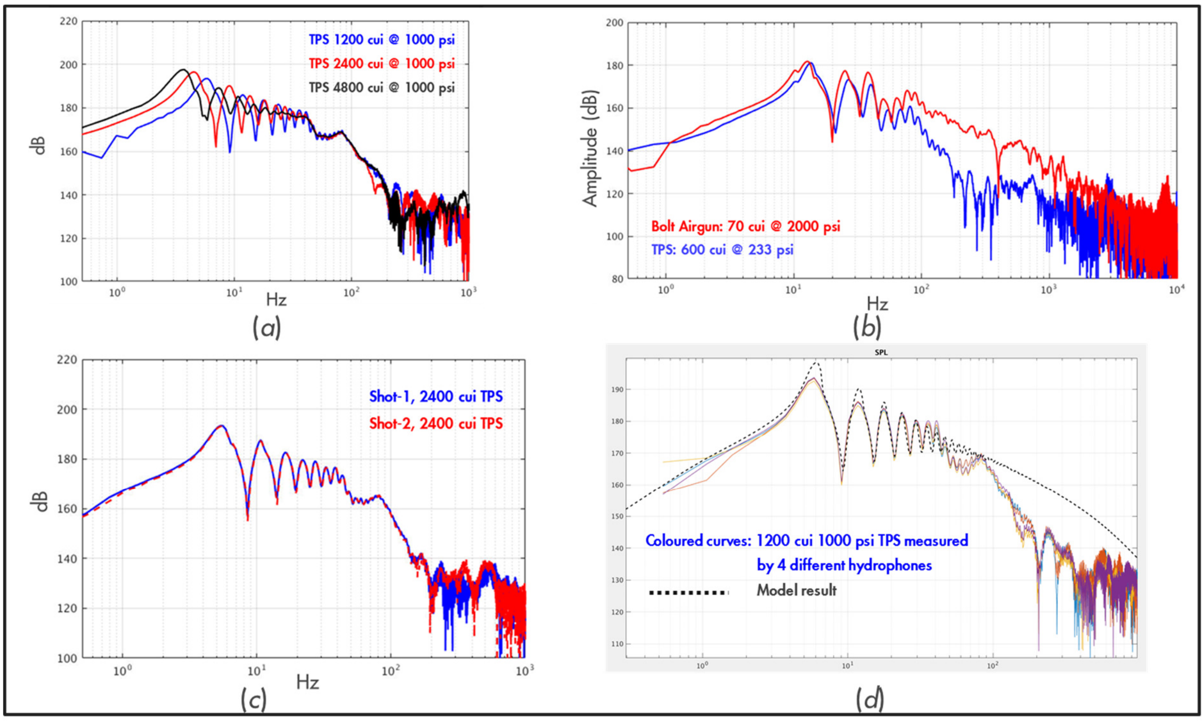

Figure 3 *(a) TPS measurements for different volumes. (b) A comparison between the TPS source and an airgun with the same energy. Note that the TPS is 30 dB weaker at 300 Hz. (c) Repeatability for a 2400 cui TPS source. (d) Modelling results and data from a 1200 cui TPS source.*

Full Waveform Inversion

One of the goals of the TPS development is acquisition of data containing sufficient low frequency energy for successful application of Full Waveform Inversion (FWI) in complex geologies. For this purpose, a 3D salt dominated velocity model from the Gulf of Mexico (Figure 4a) was used to generate a synthetic Ocean Bottom Node data set with nodes on a 1 by 1 km grid and sources on a on a 50x250m grid. We used a wavelet with a flat spectrum between 0.5 and 6 Hz. For our FWI tests we used a starting model which was 5% off everywhere. A reference FWI result was obtained by assuming a noise-free environment. An example of the resulting FWI update using a 1.2-1.4 Hz frequency band is shown in Figure 4b. We subsequently convolved the synthetic data with the modeled signature of a 20 kcui TPS, added realistic noise levels as measured on Ocean Bottom Nodes from the Gulf of Mexico and ran the FWI again on the 1.2-1.4 Hz frequency band. It is observed that the TPS synthetics lead to a velocity update closely resembling the noise-free reference update (Figure 4c). Further modeling studies are being performed to investigate the quality of the velocity updates and to compare the TPS with other marine sources.

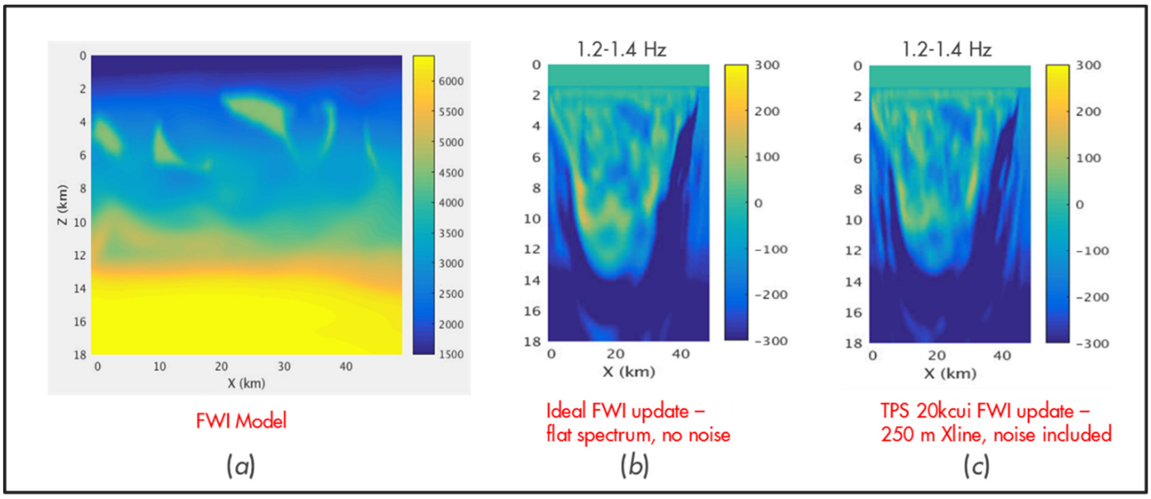

Figure 4 *(a) The geological model, (b) ideal noise-free FWI update using a 1.2-1.4 Hz frequency band and (c) result over the same frequency band with a TPS 20 kcui source and representative noise added.*

Conclusions

A new marine seismic source (Tuned Pulsed Source; TPS) is being developed which aims at improving the low frequency content of the recorded wavefield, while providing environmental benefits by a reduction in the high frequency output. Initial field tests demonstrate the viability of this source. The outgoing wavefield` from the TPS source can be modeled accurately within the seismic bandwidth. Initial synthetic results suggest that a 20 kcui TPS source will be beneficial for Full Waveform Inversion.

References

Hegna, S. and Parkes, G. [2011] The low frequency output of marine air-gun arrays. *81th SEG Annual Meeting*, Expanded Abstracts, 77-81.

Plesset, M. S. and Prosperetti, A. [1977] Bubble dynamics and cavitation. *Annual Review of Fluid Mechanics* **9**, 145 – 185.

Ronen, S. and Chelminski, S. [2017] Tuned Pulse Source – a new low frequency seismic source. *87th SEG Annual Meeting*, Expanded Abstracts, 6085-6088.

ten Kroode, F, Bergler, S., Corsten, C., de Maag, J.W., Strijbos, F. and Tijhof, H. [2013] Broadband seismic data – the importance of low frequencies, *Geophysics* **78**, WA3-WA14.

Ziolkowski, A. [1970] A method for calculating the output pressure waveform from an air gun. *Geophysical Journal of the Royal Astronomical Society* **21**, 137 – 161.