An empirical relationship between surface reflection coefficient and source array amplitude

Les Hatton
Oakwood Computing Associates Ltd. and Kingston University, London*

January 1, 2007

Abstract

This paper investigates the anelastic response of the sea surface using airgun data recorded at different depths in a specialist experimental facility and provides a model for predicting the surface reflection coefficient given the zero to peak pressure output of the array and deployment depth.

1 Overview

Close observation of the sea surface when a marine seismic source is fired reveals a complex disruption of the surface caused by the impact of the direct pressure wave. This disruption appears almost immediately corresponding to the distance travelled divided by the velocity of sound in sea water and is usually known as the 'shot effect', [3]. For a typical marine seismic airgun array, this would correspond to around 4 msec. It should not be confused with the appearance of the bubble in the case of airgun arrays. The bubble from an airgun tends to rise like a spherical cap bubble with an aggregate velocity of around 1m/s and so appears at the sea surface after several seconds. Figure 1 illustrates this well. The evacuation of the air from the further of the two guns firing here which will be transformed into a rising bubble can be seen clearly even though the disruption of the surface is already evident. If the disruption is viewed at very close quarters it appears as a thin mist to a depth of several cm punctuated by narrow towers of water of a similar height.

It is also evident here that the disruption is limited to a cone of approximately 20 degrees half-angle (a surface disruption of diameter approximately 2m with guns deployed here approximately 3m below the surface.) This paper will not attempt a detailed mathematical model of this phenomenon as relatively little is known about it. For example, it might be thought that the size of the effect would be related to the tensile strength of water but estimates of this vary dramatically between around 1 bar and several hundred bars, ([4], [5]), but the effect appears much more consistent than this. Moreover, as the data itself shows, the effect is not small.

*L.Hatton@kingston.ac.uk, lesh@leshatton.org

Figure 1: The shot-effect at close quarters revealing the direct disruption of the surface significantly before the bubble breaks the surface. Here the air evacuation of the furthest firing airgun can be clearly seen under the water whilst the shot effect on the surface is already well developed.

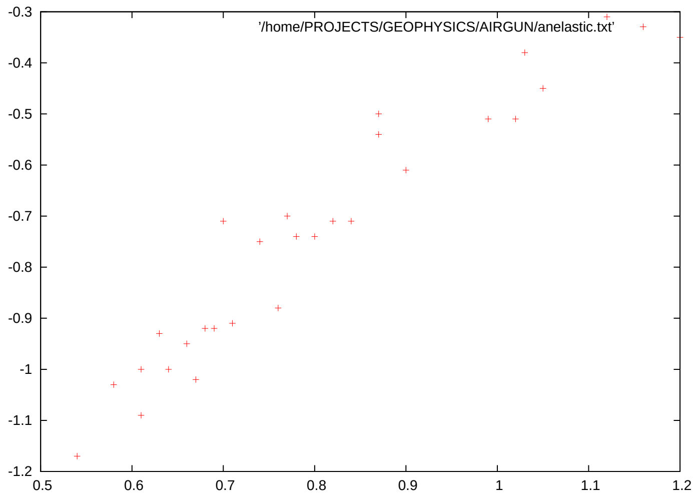

Figure 2: Empirical reflection coefficient v. normalised pressure

It should be pointed out that this is fundamentally different from the work of [1], which is based on the scattering effect of a wavy surface. In such a model, no energy is lost, it is simply redirected. When the surface behaves anelastically energy is lost from the acoustic field and converted into work done on fracturing the surface in some complex manner. Even though the physical mechanism is very complex, a simple and very elegant result can be used to predict the total energy as will be discussed later.

2 Data collection

The data was kindly supplied by WesternGeco and was acquired in 2005 in a specialist deep-water facility using both single guns and multiple gun clusters for deployment depths in the range 1-10m. The actual data is shown in Figure 2 plotted using a normalised pressure axis of:-

$$(\frac{p}{d^2})^{1/5} \tag{1}$$

where p is the zero to peak pressure in bar-m measured in the bandwidth 0-512Hz and d is the depth in metres at which the source is deployed. The following relationship gives a good linear fit:-

$$r = 1.3(\frac{p}{d^2})^{1/5} - 1.7 \tag{2}$$

where r is the reflection coefficient and is constrained to the range (-1.0, -0.3).

It can be seen that some of the measurements correspond to a reflection coefficient estimate of smaller than -1.0. In a flat surface, this is impossible, so it is likely that these are caused by focusing effects, which are probably responsible in part for the scatter of the data. The mechanism is described in more detail in [1]. Using the model of Jovananovich et al with an averaged dominant airgun frequency of 35Hz for the deployed clusters and a rms wave height of up to 0.5m taken from the field logs, a variation of ± 0.06 in reflection coefficient is obtained for the focusing / defocusing effect. Most of the departures from linearity can be explained by this giving some confidence in the predictive power of the empirical model proposed here.

3 Application

It is debatable how this effect should be incorporated. It is traditional to apply a scalar value > -1.0 for the reflection coefficient to the entire signature to provide the virtual image. In the case of surface anelasticity, this makes the assumption that the behaviour of the surface is constant for the effective duration of the signature. The effective duration of an airgun signature is typically around 150msec to include the peak and first bubble but it is far from clear that the anelastic surface behaviour is constant during this phase and it may be that the behaviour is best characterised by clipping only when the pressure field exceeds some tensile limit and after a quick recovery, returning to the ideal case of -1. Further refinement along these lines must await a more detailed set of experiments, particularly for higher frequencies as they become of interest for environmental impact reasons.

4 Acoustic energy loss at the free surface

If the assumption of a scalar value for the reflection coefficient is made, then the following elegant result due to [2] can be used to estimate the acoustic energy loss at the surface due to this anelastic behaviour.

$$E_{loss} = \frac{4\pi}{\rho c}\frac{1-r^2}{2}R_{ss}(0) \tag{3}$$

where E_{loss} is the acoustic energy lost in joules, ρ is the density, c is the velocity of sound, r is the reflection coefficient and $R_{ss}(0)$ is the zero lag value of the autocorrelation of the near-field source signature. For the range of reflection coefficients found empirically here the total acoustic energy loss due to anelastic reflection was as high as 46% for the shallowest deployments.

5 Conclusions

In a high quality experimental dataset it was found that the reflection coefficient r was linearly dependent on:-

$$(\frac{p}{d^2})^{1/5} \tag{4}$$

within the range of values $r \subset (-1.0, -0.3)$. In addition, most of the departures from linearity could be explained by focusing / defocusing effects of a wavy surface using the work of [1].

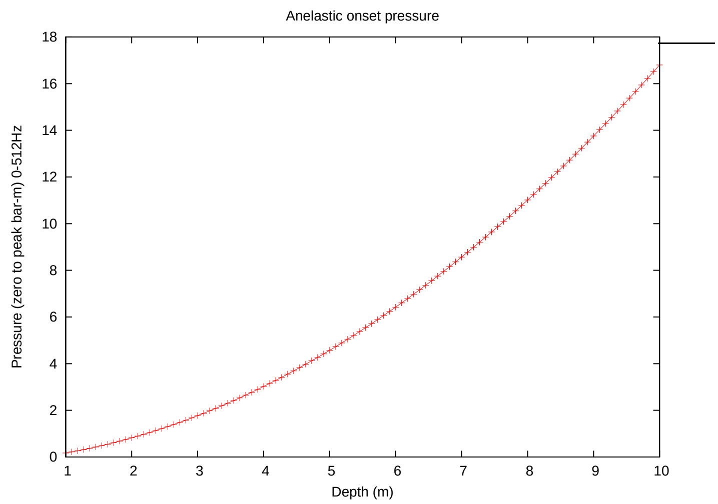

Figure 3: Approximate minimum zero to peak pressure in bar-m in the 0-512Hz band for which anelastic behaviour starts as a function of the depth in m.

Furthermore, anelastic effects begin to appear whenever the following is true.

$$\left(\frac{p}{d^2}\right)^{1/5} \gtrsim 0.7 \tag{5}$$

or

$$p \gtrsim 0.168d^2 \tag{6}$$

Using this relationship, the approximate zero to peak pressure in the bandwidth 0-512Hz for which anelastic behaviour starts is shown in Figure 3 as a function of the depth.

The implication is that many commonly used marine seismic sources will clip the ghost to some extent. Some clipping is usually considered beneficial as it fills up the ghost notch in the amplitude spectrum a little and reduces the gain of a deconvolution filter here helping to control noise amplification. However given the magnitude of the acoustic energy loss described above, the implication certainly for shallow surveys is that much weaker sources could be used without penalty as a significant amount of the excess power is used in simply warming up the sea surface a little.

6 Conclusions

Studies such as this are critically dependent on good experimental data quality. The author would like to thank Morten Svendsen and Elaina Hurst of WesternGeco for kindly making such a high quality dataset available.

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