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CHARACTERISATION OF AN AIR-GUN AS A SOUND SOURCE FOR ACOUSTIC PROPAGATION STUDIES

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ABSTRACT

The prediction of underwater acoustic propagation is important strategically and tactically in undersea warfare as it is a critical parameter in determining detection range. In the relatively shallow waters of the continental shelves the acoustic properties of the seabed become the dominant factor but there are only a few locations where the relevant properties have been adequately determined.

This paper concentrates on an investigation of the suitability of a shallow air-gun sound source as a source for acoustic propagation and seabed characterisation studies. It particularly focuses on an experiment that aimed to determine to what degree the combination of the direct and surface reflected signals from a shallow air-gun could be predicted from measurements of the air-gun signal made with a hydrophone close to the air-gun. Air-guns are impulsive sound sources that are commonly used in seismic exploration where the main interest is in vertical propagation into the seabed to depths of several kilometres. For acoustic propagation studies it is near- horizontal propagation in the acoustic wave-guide that is important so the requirements are different from the seismic case.

INTRODUCTION

Air-guns are underwater sound sources that operate by suddenly releasing a volume of compressed gas (usually air or nitrogen) into the water. The gas forms a bubble which initially expands rapidly, creating a sharp impulsive noise (the primary pulse), and then oscillates with decaying amplitude, creating an oscillatory signal known as the bubble pulse. The resultant acoustic signal is omni-directional, highly repeatable and produces high acoustic source levels at the bubble pulse frequency (typically around 20 Hz) and its harmonics up to at least 500 Hz (Veerbeek and McGee (1)). Figure 1 shows a typical air-gun signal and its spectrum.

When compared to an explosive source an air-gun has a somewhat lower source level and a lower upper frequency limit, but has the advantage that it can be operated at a high repetition rate. For experimental work on small vessels the repetition rate is usually limited by the size of the compressor used to supply the gun, with typical repetition periods being around 10 seconds. This means that hundreds of shots can be recorded on a transect instead of the 5 to 20 shots typically obtained with SUS charges.

One of the primary limitations of an air-gun sound source is that the efficiency of the air-gun drops off markedly as the ambient pressure becomes significant compared to the pressure of the gas supplied to the air-gun. This effect limits the operational depth of an air-gun to a few hundred metres but the practical difficulties of providing a continuous gas supply to a deep air-gun means that it is more cost-effective and convenient to operate the gun at depths of less than ten metres. The direct signal from a source at these shallow depths overlaps and interferes with the surface reflected signal, producing an effective source which has directionality in the vertical plane. For propagation studies it is necessary to be able to predict the source strength and vertical-plane beam pattern of the effective source and this paper presents the theory for making this prediction and the results of an experiment designed to determine how well this can be done.

THEORY

The prediction of the signal received by a hydrophone at any location due to the combined direct and surface reflected signals from the air-gun is straight forward providing the geometry is known, the sea surface can be considered to be a flat surface at the wavelengths under consideration, and the pressure signature of the air-gun is known. The latter can most conveniently be determined by placing a hydrophone, called a near-field hydrophone in this paper, close to the air-gun (say 1m away), so that the signal it receives is dominated by the direct path signal. The surface reflected signal can then be removed from the near-field hydrophone signal by de-convolution (see below). Figure 2 shows the geometry used for the calculation.

The pressure signal received at the hydrophone is

$$s(t) = \frac{1}{r} p\left(t - \frac{r-1}{c}\right) + \frac{R}{r'} p\left(t - \frac{r'-1}{c}\right) \tag{1}$$

Where:
r is the distance of the hydrophone from the source (m),
r' is the distance of the hydrophone from the ghost source (ie surface reflected image, m),
R is the pressure reflection coefficient for a reflection from the sea surface (usually -1),
c is the speed of sound (m/s),
t is time (s), and
$p(t)$ is the pressure signal due to the source only, referred to a distance of 1m from the centre of the source (Pa).

Equation 1 applies to the near-field hydrophone and to a hydrophone placed a long way from the air-gun (a far-field hydrophone), the difference being that in the near-field case r << r' so that the first term dominates whereas in the far-field case r and r' are very nearly equal and so both terms have similar magnitude.

Although the effect of the surface reflection on the near-field hydrophone signal is small it can be removed using the following iterative procedure:

$$p_i(t) = rs\left(t + \frac{r-1}{c}\right), \quad i = 0$$
$$p_i\left(t - \frac{r-1}{c}\right) = rs(t) - \frac{rR}{r'} p_{i-1}\left(t - \frac{r'-1}{c}\right), \quad i = 1,2,3....$$
(2)

An alternative method, which gives equivalent results and has the advantage of being significantly faster to compute, is to make the correction in the frequency domain. The starting point is to re-express Equation 1 as:

$$s(t) = \frac{1}{r} p\left(t - \frac{r-1}{c}\right) * (\delta(t) + \delta(t - \tau))$$
(3)

where:
$*$ represents the convolution operation,
$\tau = \dfrac{r'-r}{c}$ and
$\delta(t)$ is the Dirac delta function.

By Fourier transforming Equation 3 and invoking the convolution and shift theorems for Fourier transforms it is straight forward to show that:

$$S(f) = \frac{1}{r} P(f) e^{-i\omega\frac{r-1}{c}} \left(1 + \frac{rR}{r'} e^{-i\omega\tau}\right)$$
(4)

Here $\omega = 2\pi f$ is the angular frequency and capital letters have been used to denote the frequency domain counterparts of the corresponding lower case time domain variables.

Equation 4 can be rearranged to solve for P(f), which can then be inverse Fourier transformed to yield p(t).

EXPERIMENTAL METHOD

The experiment reported here was carried out on the 23rd of April 1999 in the vicinity of 32°20'S, 114°58'E, approximately 30 nautical miles west of Rockingham, Western Australia. The water depth at the site was approximately 500 m. There was a 2 m swell from the SW and a 1.5 m sea from the SE with winds of 15-20 knots from the SE. Some 800 shots were recorded at ranges varying from 70m to 6 km.

The sound source used in the experiment was a Bolt PAR model 600B air-gun which was fitted with a 20 cubic inch (3.28×10^{-4} m^3) firing chamber and operated at a pressure of 10 MPa. The air-gun was mounted in a tow-fish and towed behind the vessel at approximately 3 knots at a mean depth of 3.8 m.

Signals were received by two hydrophones on a drifting recording package. The hydrophones were at depths of 21 m and 46 m and two digital audio tape (DAT) decks in an underwater housing were used to record each hydrophone with two different gain settings. Each DAT deck recorded both hydrophones so that the relative arrival times at the hydrophones could be determined. A sonobuoy hydrophone was located next to the upper hydrophone and cabled to a sonobuoy radio transmitter on the surface.

A two-channel DAT tape deck on board the vessel recorded the signal from the near-field hydrophone which was mounted on the tow-fish 0.87 m from the air-gun's exhaust ports. The other DAT channel was used to record the output from the sonobuoy receiver. This allowed the distance from the source to the drifting package to be determined from the time difference between the near-field hydrophone and sonobuoy signals. A CTD cast was made to a depth of 200 m to enable the sound velocity profile to be computed.

Two deployments of the drifting package were made, the first for 3.5 hours and the second for 1.5 hours. Fifty minutes into the first deployment the sonobuoy hydrophone failed and no further useful sonobuoy signals were received for the remainder of that deployment. The failed hydrophone was replaced with a spare before the second deployment and operated satisfactorily for the rest of the experiment. Source to drifting receiver separations varied between 100 m and 6 km for the first deployment and between 80 m and 3 km for the second deployment.

EXPERIMENTAL RESULTS

Near-field hydrophone signals for a typical shot are shown in Figure 3 and clearly show the expected structure of an initial impulse followed by a gradually decaying component due to the bubble oscillation. The signals were consistent from shot to shot except for slight differences in the bubble oscillation frequency caused by changes in hydrostatic pressure due to the effect of surface waves.

An expanded view of the initial impulse is also shown in Figure 3. Here a high frequency noise component appears to be superimposed on the expected signal but, unlike true noise, it is consistent from shot to shot. Inspection of the far-field hydrophone signals indicated that this high frequency component was not radiated into the far-field to any significant degree. A plausible explanation is that when the air-gun fired it caused the tow-fish to vibrate and these vibrations then coupled mechanically to the hydrophone.

Figure 4 shows a comparison between the measured and predicted far-field time domain signals at the deep hydrophone for a shot at a range of 107m. In general the agreement was good but the predicted signal had more high frequency noise than the measured signals. The high frequency noise was directly attributable to the high frequency noise component in the near-field hydrophone signal discussed above. At longer ranges the high frequency noise signal dominated the predicted signal and it was necessary to filter the signals using a high order low-pass filter with a 500 Hz cut-off frequency in order to provide a meaningful comparison. The filtered signals agreed well with the measured signals whenever there was adequate signal to noise ratio in the measured signal to provide a meaningful comparison.
A comparison of the same signals in the frequency domain is given in Figure 5. Generally the predicted and measured spectra agreed to within a few dB in the frequency range 20 Hz to 400 Hz although there were larger discrepancies at frequencies corresponding to nulls in the bubble pulse spectrum (eg 32 Hz, 64 Hz). There was also a spectral notch in the predicted signal at about 250 Hz which was not seen in the measured signal. This originated from a spectral notch in the signal recorded by the near-field hydrophone which appears to have been due to the high frequency noise component.

Figure 6 shows the mean and standard deviation of the dB differences between the predicted and measured signals for both hydrophones as a function of frequency for 42 shots at ranges varying from 80 m to 1000 m. These results covered depression angles (from the horizontal) ranging from 1.1° to 13° for the shallow hydrophone and from 2.4° to 28° for the deep hydrophone and were for the vessel steaming away from the recording package. In the frequency range 20 Hz to 200 Hz the shallow hydrophone signal was under-predicted by about 2.5 dB and the deep hydrophone signal was over-predicted by about 1.5 dB. Standard deviations were greater for the shallow hydrophone which was subject to a higher level of flow noise than the deep hydrophone. The effect of the spectral notch in the predicted signal at 250 Hz can be seen and at frequencies above 400 Hz the discrepancies between the measured and predicted signals became large. The discrepancies at high frequencies were expected because at these frequencies the height of the surface waves was a significant fraction of the acoustic wavelength and therefore the assumption of a plane water surface was no longer valid.

Equivalent results for the case of the vessel steaming towards the recording package showed similar trends although the mean prediction errors for both hydrophones were 1.5 dB higher than for the departure run. The reason for this discrepancy is not known although there is evidence of a systematic change in air-gun depth due to a change in vessel speed through the water due to the vessel steaming either into or with the 2 m swell. The standard deviations of the prediction errors were also slightly larger for the approach run although this is attributable to the larger vessel motion, and hence air-gun motion, experienced with the vessel travelling into the sea.

CONCLUSIONS

Whenever there was sufficient signal to noise ratio in the measured data, predicted far-field signals agreed with measured signals to within a few dB over the frequency range 20 Hz to 200 Hz. Noise in the near-field hydrophone signal, believed to be due to vibration of the tow-fish, degraded the predicted signal at frequencies above 200 Hz. Above 400 Hz there were marked differences between the predicted and measured signals, presumably due to the breakdown of the flat water surface assumption.

There was a systematic difference between measurements made with the shallow and deep far-field hydrophones of about 4 dB which implies either a calibration error, or a change in the sensitivity of the shallow hydrophone due to it being mounted close to an air filled housing There were also systematic differences of a few dB between results obtained during approach and departure runs. This may be related to systematic differences in air-gun depth.

These results showed that the characteristics of the effective source formed by a shallow air-gun and its surface reflected image could be predicted from measurements made with a single hydrophone located close to the air-gun. In the prevailing conditions of a 2 m swell and 1.5 m sea the prediction had an adequate level of accuracy for most acoustic propagation studies over a frequency range extending from the air-gun's bubble pulse frequency (20 Hz) up to at least 200 Hz. Improvements in the near-field hydrophone mounting arrangements to isolate the hydrophone from mechanical vibrations of the tow-fish may have extended the upper frequency limit as far as 400 Hz.

The high repetition rate offered by air-guns is a major advantage of these sources when compared to explosives, as is their high degree of repeatability, relatively low running costs and much reduced safety requirements. The ability to predict the characteristics of shallow air-gun sources, as demonstrated by this project, makes them a very attractive source for this kind of work.

ACKNOWLEDGEMENTS

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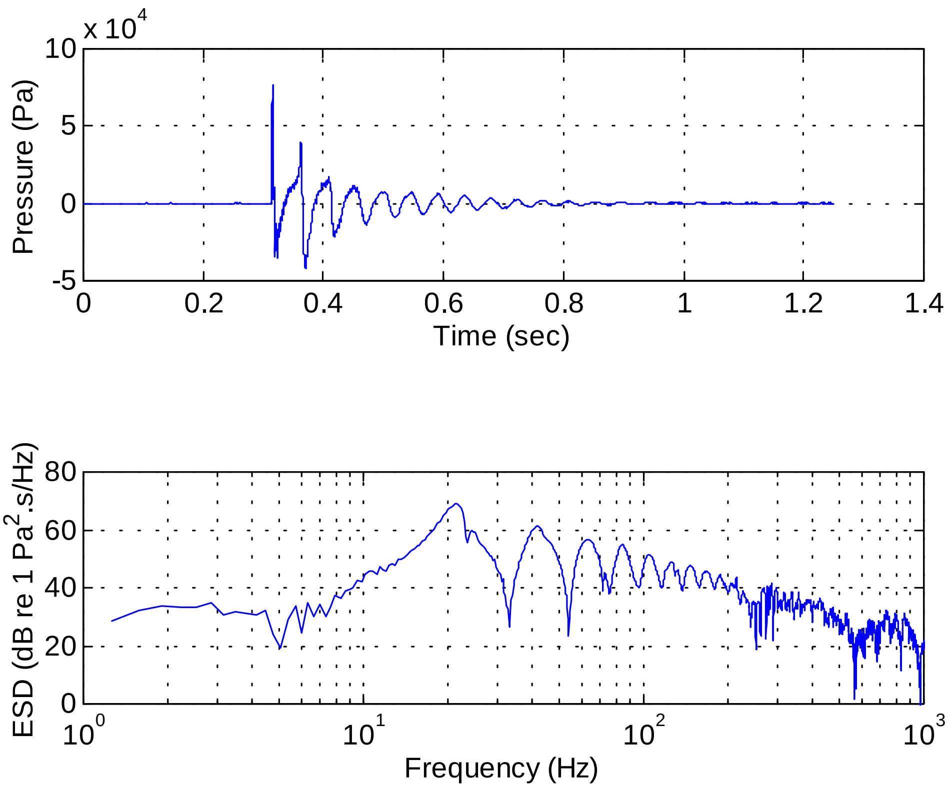

Fig 1. Typical signal from an air-gun and its energy density spectrum

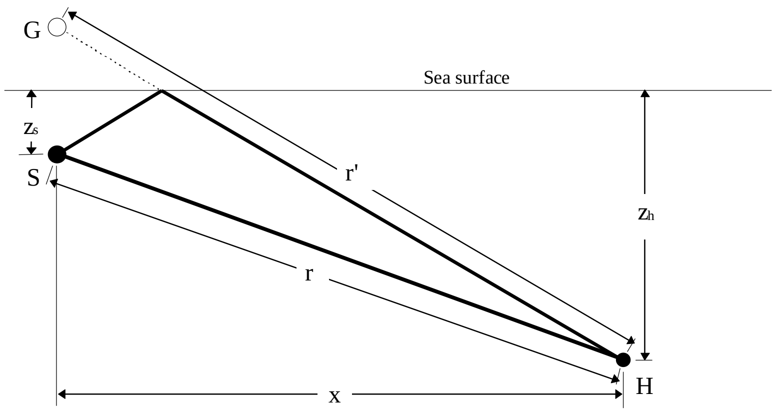

Figure 2. Geometry for calculation of received signal due to direct path and surface reflection. S is the source, G is the ghost or image source caused by reflection at the sea surface and H is the receiving hydrophone.

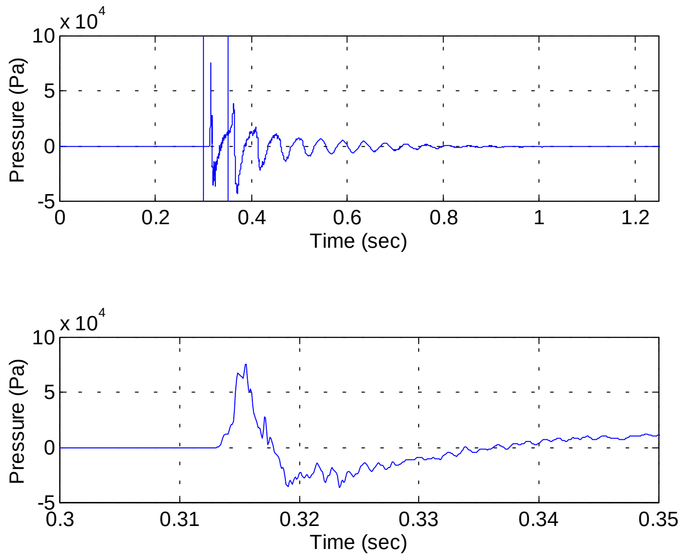

Figure 3. Near-field hydrophone signal and expanded signal

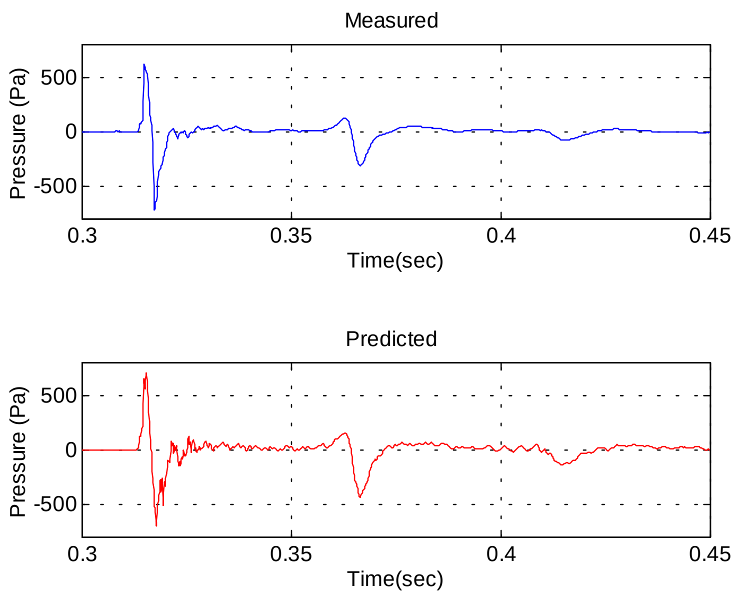

Figure 4. Time domain comparison of predicted and measured signals for a shot at 107 m range, a gun depth of 3.6 m, and a hydrophone depth of 46 m.

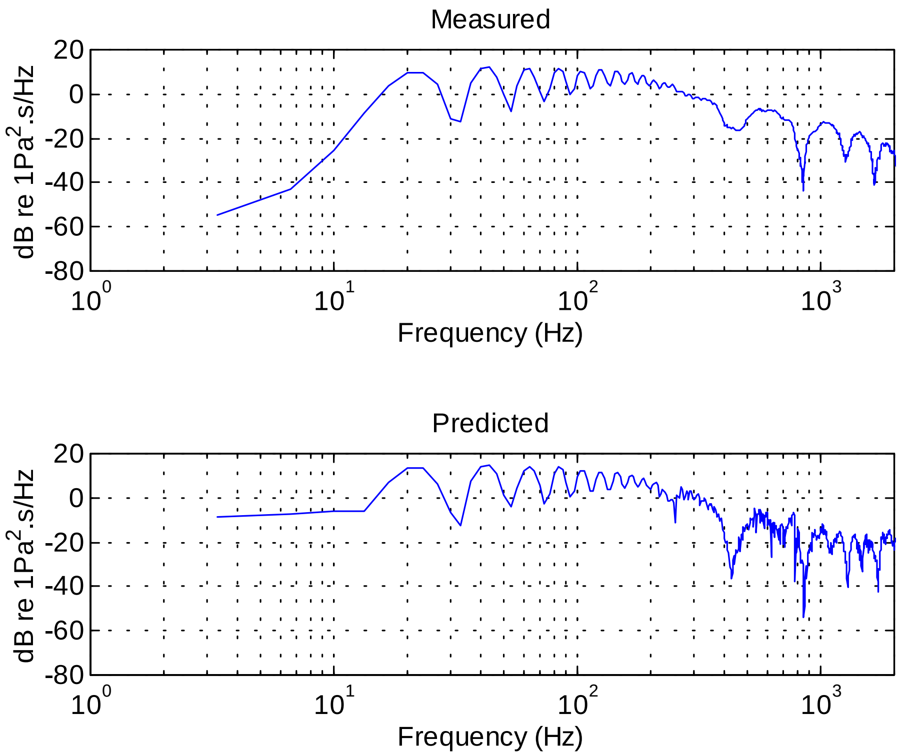

Figure 5. Frequency domain comparison of predicted and measured signals for a shot at 107 m range, a gun depth of 3.6 m, and a hydrophone depth of 46 m.

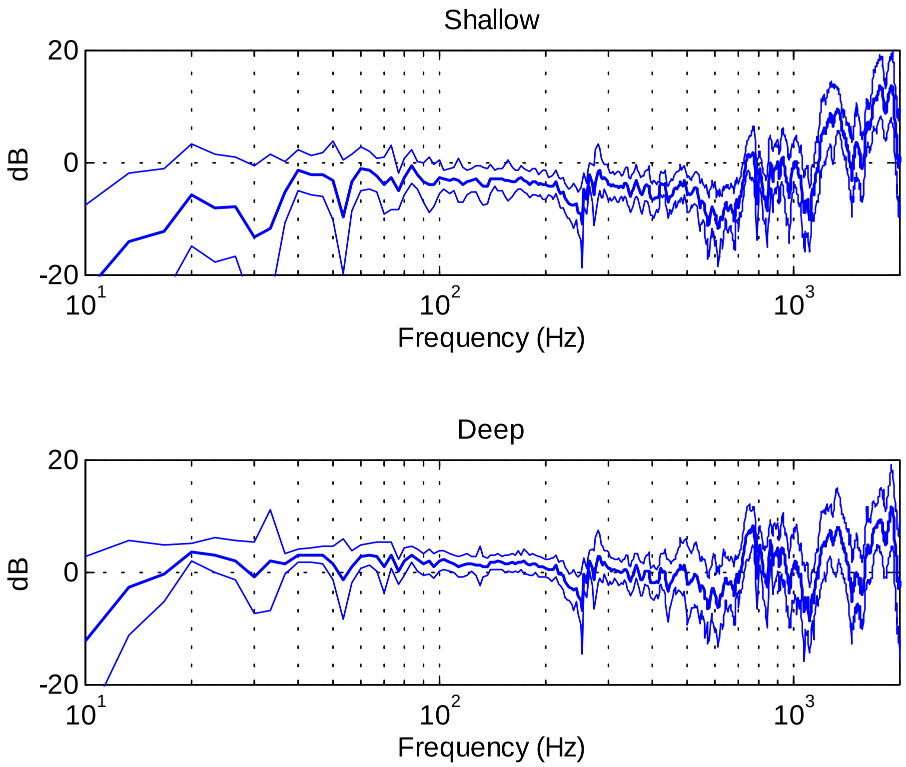

Figure 6. Thick line is mean of the dB differences between the predicted and measured signals as a function of frequency for 42 shots at ranges varying from 80 m to 1000 m Thin lines are mean +/- 1 standard deviation. Top plot is for shallow hydrophone, bottom plot is for deep hydrophone.