Theoretical Examination of the Absorption of Energy by Snow Crabs Exposed to Seismic Air-gun Noise: Stage 3 - More Realistic Treatment of Sound Sources

Dr. G. R. Lee-Dadswell
Department of Math, Physics and Geology
Cape Breton University
Sydney, NS, Canada, B1P 6L2

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Executive Summary

This research group has been carrying out theoretical studies to evaluate whether it is likely that snow crabs could suffer physical damage from exposure to the intense sound that occurs during a seismic shoot. A criticism of the results of the two previous reports [13, Lee-Dadswell, 2008] and [14, Lee-Dadswell, 2009] produced by this research group has been that the treatment of the sound source was very simplistic in those studies. The work reported upon here was a project to treat the sound arriving at the crab from an air gun array in a more realistic manner.

This has involved several main lines of inquiry:

1. Cases were found in which simple wave superposition theory could be applied to estimate sound levels in the vicinity of an air gun array. These calculations result in a revision to the estimate of the maximum sound intensity likely to be experienced by crabs. For crabs on the bottom in 50 m of water the new upper limit estimated is 239 dB. This estimate does not include reflections from the water surface or from the seabottom and so it is likely somewhat low. This should be compared with the previous estimate of 255 dB.

2. The dynamics of the air bubble produced by an air gun have been modeled. This gives this research group the ability to predict signatures of individual air guns.

3. Computer tools have been developed which allow us to predict the details of the sound field at any point around an air gun array. This calculation is extremely computationally intensive and has only been carried out for a few "proof of principle" cases. However, these allow us to verify that the simpler calculations described above are reasonable.

In light of the new estimates of sound levels that crabs could be exposed to the conclusions of [14, Lee-Dadswell, 2009] have been reassessed. We find that the results of the present study do not change the conclusions previously reported:

- Crabs are unlikely to suffer damage to bulk tissues as a result of seismic shoots.

- The separation of membranes reported in [1, Chadwick, 2004] are plausible. This may be a matter of concern but more study by biologists would be required to determine what effect this has on the health of snow crabs.

This research has been somewhat hampered by a lack of available data on real air gun signatures. Aside from a very small amount of data that is in the open scientific literature, air gun signatures are mostly proprietary information.

Introduction

Offshore seismic surveys have many potential impacts on fisheries and on the environment in general. The sound generated during a seismic survey can be sufficiently loud that various marine organisms may be affected. Considerable work has been done on the effects on marine mammals (e.g. [7, Goold, 1998]). Some work has also been done on fish which are vulnerable because of their air bladders. Comparatively little work has been done to determine the effects on marine invertebrates. At present in Nova Scotia there is particular concern that seismic surveys might have detrimental effects on snow crabs [1, Chadwick, 2004], [18, Moriyasu, 2004], [24, Walmsley, 2007].

The possible effects which are envisioned [24, Walmsley, 2007] range from subtle behavioural and environmental effects which might affect catchability, through intermediate behavioural effects which could affect reproductive or feeding success, through to immediate, direct physical damage. Previous experimental studies have been carried out [1, Chadwick, 2004] to try to assess whether physical damage was sustained by crabs in the viscinity of a seismic survey. However, these studies were largely inconclusive. Among the reasons for this are:

- The sound levels that the crabs were exposed to may have been below the levels at which physical damage might be expected.
- There is insufficient knowledge of what types of physical damage ought to be expected.
- There is insufficient knowledge of the physiology of a healthy crab for damage to be recognized when it has occurred.
- Differences between test and control groups may have been caused by factors other than exposure to seismic pulses [1, Chadwick, 2004].

Earlier theoretical study [13, Lee-Dadswell, 2008], [14, Lee-Dadswell, 2009] concluded that even the highest intensity sound produced in a seismic survey is probably insufficient to cause direct physical damage in the form of tissue tearing or crushing. However, the displacements predicted might be sufficient to cause some of the subtle physical damage that was tentatively identified in [1, Chadwick, 2004]. In particular, stresses at boundaries between organs and membranes on the outsides of those organs may be many orders of magnitude larger than the elastic limits of the tissues.

This is a theoretical study in which classical acoustics theory is used to predict sound levels inside a simple model of a crab. In all earlier studies of this nature [21, Stanton, 1990], [13, Lee-Dadswell, 2008], [14, Lee-Dadswell, 2009] the incoming sound has been treated as a plane wave and little attention has been payed to calculating the correct frequency dependent amplitude of this wave. The present study was carried out to correct this. Hence the focus on this study will be on modeling the source (individual air guns and arrays of air guns) and one using a better knowledge of the source to produce a better picture of the incident sound field on the bottom under an air gun array. Comparatively little attention will be paid to improving the model of the crab itself. Stage 4 of this project is now ongoing. It will aim to make further refinements of the modeling of the crab. A final report on stage 4 will be available in 2011.

Objectives

In previous studies [13, Lee-Dadswell, 2008], [14, Lee-Dadswell, 2009] a model was developed and used to examine the motion of tissues inside a crab exposed to sound from air guns. The model had a number of major simplifications in order to make the calculations tractable.

1. The sound from the air guns was treated as a plane wave. This is expected to be a good approximation for source distances that are large compared to the air gun array (i.e. in deep water).
2. The crab is treated as spherical.
3. The crab carapace is treated as a thin, uniform elastic shell.
4. The interior of the crab (tissues) are treated as a uniform elastic solid with very small shear modulus.
5. No damping (viscosity or viscoelasticity) is included in the model.
6. The seabottom is neglected.
7. Linear acoustics is assumed to be valid (no coupling between modes).

This was already an improvement over studies that can be found in the literature [21, Stanton, 1990] which treat the interior of the crab as a liquid.

The present study aims to treat the incoming sound from the airguns more realistically. Two main issues need to be addressed. First of all, the previous calculations simply treated the incoming wave as having arbitrary amplitude. The response of the crab was calculated as a multiple of this arbitrary amplitude. On one hand this is a valid approach since the response at any given frequency is dependent only on the amplitude (technically called spectral density) of the incoming sound at that frequency. So the crab's response can be calculated one frequency at a time. The results can then be rescaled according to the spectral densities and simply added. However, the spectral densities are not known and are not available in the literature since they are proprietary. This has hampered our ability to do the correct rescaling of the response of the crab tissues. As a result, in the previous work a very crude approach needed to be taken. The responses over all frequencies were simply averaged. Thus, the main goal of this study is to model the dynamics of the bubble produced by an air gun and use this to predict the spectral density of an air gun signal. Our expectation was that doing this was likely all that would be possible in the short time of this project. This goal has been achieved. As will be discussed below we have actually been able to go considerably further than this in improving the modeling of the incoming sound.

A secondary goal was to make further improvements to the Maple sheets and start making them more usable to researchers who do not have expertise in Maple. But it was stated in the original proposal that it was unlikely that significant progress could be made in this area. We have now produced a number of Maple sheets which could be used, with minimal training, by researchers with no Maple expertise. These sheets are not very flexible yet and we have not started to build a user interface. The sheets we currently have would be useful to other researchers studying sound incident on spherical objects. For the sheets to be useful to a broad range of researchers work would need to be carried out on several fronts.

1. A user interface would need to be built.
2. The sheets would need to be much more flexible. At minimum, to be useful they should be able to handle cylindrical as well as spherical symmetry and they should be able to model a system with any number of concentric shells.

Both of these will require a large amount of work. Progress is expected during the newly funded project of this research group. However, it should be pointed out that improvement of the Maple sheets is not the primary goal of the new project.

Approach

Simple First Approximations

The System of Study

It is hard to have a sense of what sorts of numbers are resonable when, for example, estimating the sound intensity level due to an air-gun array at some point far from the array. Therefore, before proceeding with a difficult calculation of this sort is it useful to do some quick "back of the envelope" calculations to establish the range of reasonable answers. This also serves as a good way to establish a detailed picture of the process being examined. Figure 1 shows the typical configuration of the system that we are examining. The crab is assumed to be below or nearly below the array. This important. We are not considering the case of a crab located many kilometers from the point where the seismic shoot is taking place. This is in contrast to many studies (e.g. [7, Goold, 1998], [16, MacGillivray, 2005]) in which the impacts on mammals and fish are predicted. It is thought for various reasons that the only risk of physical damage to crabs would be in the case where the crabs are directly underneath, or very nearly directly underneath, the air-gun array. If biological studies are undertaken to examine behavioural effects on crabs then it may be useful at that time to predict sound levels far from the air-gun array. Because we are not examining the sound levels at large distances from the array we do not have to take into account multiple reflections off of the bottom/surface or channeling due to temperature and salinity profiles as these will have little impact on the propagation of sound almost directly downward from the array. Nor do we need to account for attenuation of the sound since in water, the sound will attenuate very little over distances of tens or hundreds of meters.

Simple Calculations

In discussions of the signatures of air gun arrays the term far field is used to refer to the distance beyond which wave interference is not an important factor. In this study we are only interested in the near field since the far field is beyond distances of several km. So we must account for interference effects. This is done via well known methods of wave superposition. In general, for a multifrequency signal from multiple sources, this can be quite complicated, especially with an array consisting of many guns. However, there are several cases, discussed in the Annexes, for which this calculation can easily be carried out.

A More Sophisticated Model

To be able to predict the incident sound field at any point around the array we must follow several steps. Very schematically these are

1. We must calculate the behaviour of the sound source. This is the air bubble that is produced by the air gun. This involves solution of a differential equation which can be carried out numerically.
2. Given the behaviour of the air bubbles we can calculate the signatures (pressure deviations) due to each air gun.
3. The resulting signatures are summed at the location of the crab.
4. The motion of the crab in response to the summed signatures is calculated as described in [14, Lee-Dadswell, 2009].

This process is described in much greater detail in the Annexes.

Findings

Outcome of Simple Calculations

For an air gun array with a "peak source intensity level" of 255 dB the sound intensity level in 50 m depth of water directly below the center of the array would be 221 dB. This neglects reflections by the surface or by the bottom and so it is probably somewhat below what the actual value would be. The calculation is presented in much greater detail in the Annexes. The conclusions of [14, Lee-Dadswell, 2009] have been reassessed in light of this. They are

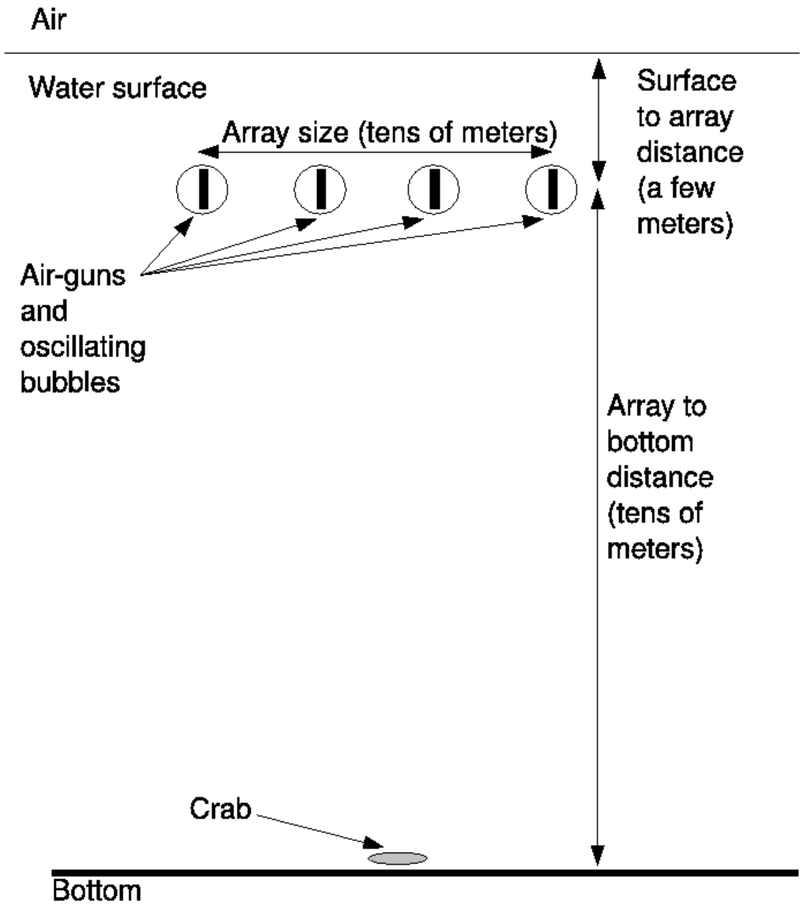

Figure 1: Typical configuration of array and crab that we are examining. The crab is assumed to be below the array, in tens of meters of water. The array is assumed to have multiple guns and to be spread over an area tens of meters on a side.

1. The earlier conclusion was that damage to bulk tissues was unlikely. Given that the new results suggest a lower sound intensity level at the crab's location, this conclusion is unchanged.

2. The possibility was found that membrane separation could happen at the boundaries of organs. The new sound intensity levels result in the predicted stresses at the organ boundary being reduced by a factor of 100. However, they were a factor of 100 to 1000 above the estimated elastic limits of typical tissues. It should be pointed out that the elastic limit of the connection between an organ and its outer membrane is certainly lower than that of bulk tissues. Thus, the conclusion that membrane separation could occur is unchanged.

So the conclusions of [14, Lee-Dadswell, 2009] are unchanged by these results. If the more sophisticated model gave us cause to reexamine the results of this simple calculation then we might have to revisit these results. However, the more sophisticated model gives us no reason to think that the simple, worst case result is incorrect.

Outcome of Analysis of Sophisticated Model

The more sophisticated model results in extraordinarily computationally intensive tasks. These can be done in principle, but the resulting computations would take months. Given the short timelines of this project, this has not been carried out. In principle we now have the capability to carry out these computations and future work is likely to include at least small scale implementations of this. A sample, "proof of principle" plot of displacement inside a crab due to incident waves from two sources is shown in Figure 2.

However, we can examine the results of the sophisticated model to check that the simple, worst case, calculation above is justified. We find that for a crab along the center line of an array the sound levels are as predicted by the simple calculation. This is unsurprising since all of the general principles (superposition of waves) in the simple calculation are applicable to the sophisticated model as well. We can use the sophisticated model to calculate the incident sound field at any point around the array. However, this simply confirms that the largest sound intensity occurs along the center line.

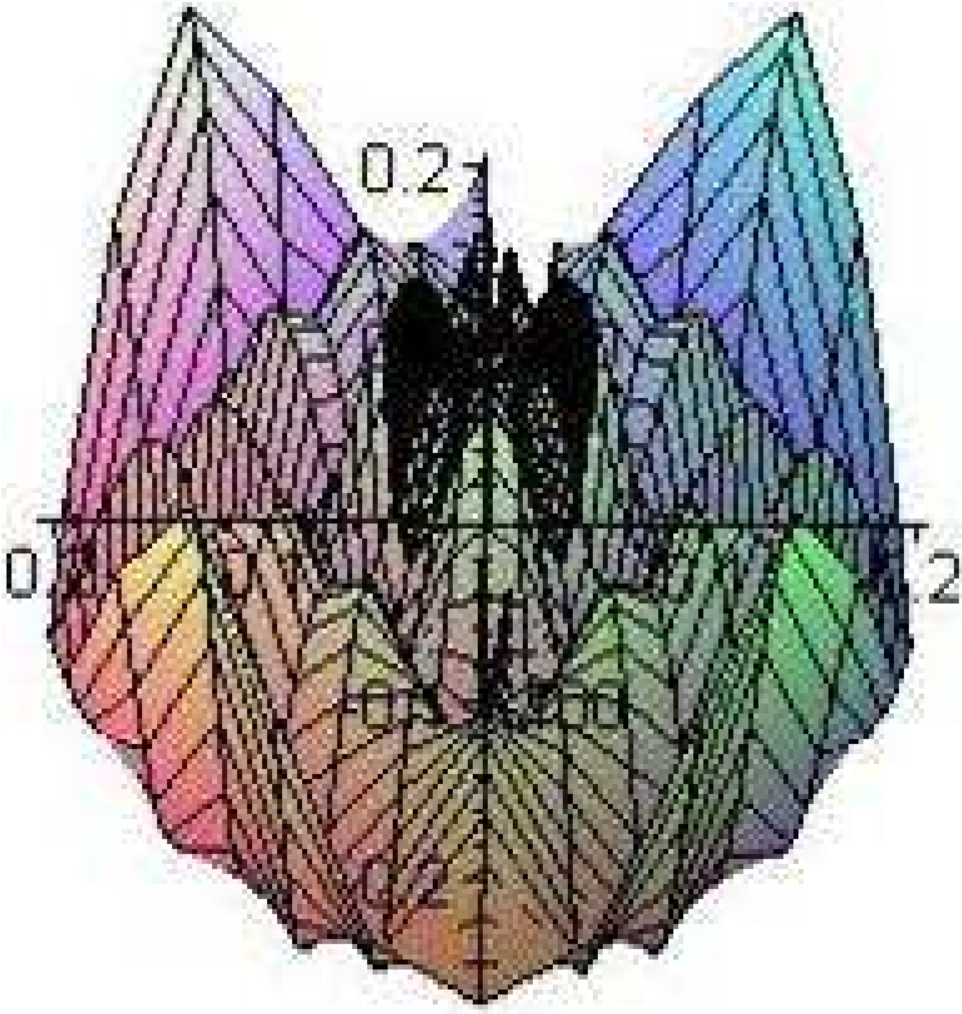

Figure 2: An example of displacement vs. positions inside the model crab due to incoming waves from two sources. The waves are each directed at a 45° angle to the vertical and are visible passing through the crab tissues. They are each constructed from a sum of two frequency components, one at $\omega = 50\ 000\ \mathrm{s}^{-1}$ and the other at$\omega = 100\ 000\ \mathrm{s}^{-1}$.

Recommendations and Conclusions

This project has produced tools that can be used to predict the sound field due to an of air guns. However, given its short timeline there has not been time to do the months of runs using these tools that would be necessary to map out this sound field. If this mapping is done it will still be a large task to explore the response of the inside of the crab when it is placed at various points within this sound field.

Nevertheless, through various simpler calculations it has been possible to draw some general conclusions. These simpler calculations, to the degree possible, have been checked using the full model that we now have at our disposal. The conclusions that can be drawn at this time are

- The conclusions of [13, Lee-Dadswell, 2008] and [14, Lee-Dadswell, 2009] are unchanged. Crabs are unlikely to suffer damage to bulk tissues, but the membrane separation reported in [1, Chadwick, 2004] seem to be possible or even likely. It is unknown what effects this would have on the health of the crabs. Study by biologists with specialized knowledge of the physiology and lifecycle of snow crabs would be necessary to determine this.

- This study has been somewhat hampered by a lack of access to data on air gun signatures. Some data are available in the literature, especially in [11, Landrø, 1992]. Most data in the literature is missing a vertical scale, and in any case working from printed graphs from papers is very limiting. A search for available data was carried out but all of the data sets found were either proprietary or protected by secrecy laws of other kinds. We have been able to compare our simulations with printed graphs of air gun signatures. But the detailed comparisons necessary for further refinement of our air gun modeling would require access to data sets that are currently not available.

- A simple worst case scenario calculation is sufficient to be able to draw the most important conclusions. This simple calculation could be expanded upon in future work based upon the methods and outcomes of our more sophisticated model. In other words, various hybrid models of intermediate complexity and power are possible.

This report has been almost entirely concerned with modeling of incident sound and little attention has been devoted to further refinements of the crab model. Presently a follow up project is under way which will further refine the crab model. In particular it is likely to lead to a model of the crab in which the crab is treated as a spheroid instead of a sphere and/or the seabottom will be included in the model. Significant assessment using finite element simulations will be carried out to guide this process and this should lead to a much better understanding of what is important to include in the crab model.

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Annexes

Wave Interference and the 255 dB "Typical Sound Level"

In general for two independent wave sources, whether the waves are sound, light or some other type of wave, if the sources have intensities, I_1 and I_2, the total intensity of waves at any point is given by

$$I = I_1 + I_2 + I_{12} \tag{1}$$

where I_{12} is called the *interference term*. The interference term is what allows us to include the effects of wave superposition. In the far field we can ignore the interference term. This is equivalent to simply adding the powers of the source together and treating the array as a single point source with this power.

However, this far field limit only applies for distances greater than approximately

$$R_{nf} = \frac{D^2}{\lambda} \tag{2}$$

where D is the longest dimension of the array and λ is the wavelength. Note that this means that the distance beyond which the far field limit applies depends on wavelength. As discussed in earlier reports ([13, Lee-Dadswell, 2008], [14, Lee-Dadswell, 2009]) we are interested in frequencies up to about 30 000 Hz. At these frequencies the wavelength is approximately 3 cm. So for the highest frequencies we are examining and an air-gun array of a typical size, $D = 20$ m the far field approximation is only valid for distances less than about 13 km.

Furthermore, in the near field, where we do have to include the interference term, the above equation for the total intensity can be incorrect if the interaction between guns is significant. If this is the case then the sources are not independent and the calculation of the actual intensities is considerably more involved. Interactions between guns are significant when the distance between guns is less than the wavelength of the sound. So for typical arrays they are important for sound below about 500 Hz.

As an example let us calculate the sound intensity levels at various locations relative to an array under various extremely simple assumptions. In particular, an oft quoted figure for the upper limit of "peak source intensity level" of an air-gun array is 255 dB rel. 1 μPa [16, MacGillivray, 2005]. It is instructive to see where this value comes from.

Various calculations [11, Landro, 1992] show that for a modest sized air-gun (150 cu. in.) the pressure deviation at a distance of 1 m is approximately ΔP =200 kPa. This yields an intensity at 1 m via the usual relation

$$I_{\text{one-gun}} = \frac{\Delta P^2}{2\rho c} = 1300 \quad \text{W/m}^2 \tag{3}$$

Typical arrays have total air-gun volumes of about 3000 cu. in. Normally, this would be done with a small number of large guns. But for sake of argument let us examine the intensity due to 20 small guns like that described above since in the far field it would make relatively little difference. At a distance of 20 km our total sound intensity level - neglecting all effects of reflections, channeling by inversion layers, etc. - would simply be

$$I_{20 \text{ gun, far field}} = 20 \frac{I_{\text{one-gun}}}{(2 \times 10^4)^2} = 7 \times 10^{-5} \quad \text{W/m}^2 \tag{4}$$

This corresponds to a sound intensity level of 143 dB. This is fairly consistent with actual measured levels at these distances [7, Goold, 1998] and with predicted levels [16, MacGillivray, 2005] especially when one considers that actual levels at such a distance could be considerably higher or lower (easily by 20-30 dB) due to the combination of attenuation, multiple reflection and channeling.

The "quoted peak source intensity level" is an estimate of how loud an entire array would be if it were a single point source and its loudness were measured from a distance of 1 m. Quoted peak source levels for air-gun arrays are usually found by taking a known intensity level at some distance and extrapolating it to a distance of one meter. Using the far field value arrived at above this yields $I_{\text{peak}} = (2 \times 10^4)^2 I_{20 \text{ gun, far field}} = 2.6 \times 10^4 \quad \text{W/m}^2$. This corresponds to a peak sound intensity level of 229 dB rel. 1 μPa. Note that this is somewhat lower than the quoted value of 255 dB. This is because peak intensity levels are usually extrapolated from measurements or calculations of intensity levels directly below the array, and in the near field. In such a location there is maximal constructive interference (the interference term is large and positive for every frequency) and the intensities are much higher.

For our example, we now need to include the interference terms for all pairs of guns. We will assume for the moment that interactions between guns are not significant. Nevertheless, in general the calculation of these interference terms can be quite difficult. However, it is simple along the line of symmetry directly down through the center of the array and at distances significantly greater than the largest dimension of the array. Under these conditions the interaction terms are simply the products of all of the pairs of intensities due to the individual guns. This is a very special case which applies only along the center line of the array because it is only here that we will find constructive interference at all frequencies. In other words, under these conditions

$$I = \sum_i I_i + \frac{1}{2} \sum_i \sum_{j \neq i} \frac{\Delta P_i \Delta P_j}{2\rho c} \tag{5}$$

where the factor of 1/2 is to compensate for double counting of all of the pairs of guns. If the guns are identical then at sufficiently large distance the individual pressure amplitudes ΔP_i are all equal. This simply gives us a number of terms that are "as if" we had an additional number of guns equal to the number of distinct pairs of real guns. In our example above, with 20 guns, there 190 distinct pairs. This has an effect essentially identical to adding another 190 guns to the array. This raises our estimate of peak intensity level to 239 dB. This is a fair bit closer to the 255 dB that is often quoted. We can find the intensity level at greater distances by simply using

$$\beta = \beta_{1m} - 20 \log(r) \tag{6}$$

This is normally valid for a point source radiating in a spherically symmetric pattern. But it remains valid for multiple sources with interference as long as the distance r is measured along an antinodal or nodal line. For our example array this yields an intensity level at a point 50 m directly below the center of the array of 204 dB. For an array with a peak intensity level of 255 dB the loudness 50 m below its center would be 221 dB.

It should be noted that 255 dB is a very high peak level and our "design" of an array containing 20 guns each of volume 150 cu. in. could not be expected to be exceptionally loud. So in spite of the crude approximations employed we are able to get reasonable ball park estimates of both near field and far field sound intensity levels. What will follow below will be a development of methods which do a considerably better job of predicting near field values.

One conclusion can already be made based on these simple calculations, especially given the results of more sophisticated calculations presented elsewhere in this report. The "worst case" tissue displacements found in earlier reports [13, Lee-Dadswell, 2008], [14, Lee-Dadswell, 2009] were unlikely to ever occur. Given that these displacements were unlikely to cause damage there is even more reason to suspect that direct damage to *bulk* tissues is very unlikely to occur. However, if the stresses at tissue boundaries calculated in [14, Lee-Dadswell, 2009] are recalculated using sound intensity levels of 221 dB or 204 dB then they are reduced by a factor of about 30 or 100. But given that the stresses predicted were of order 100 or 1000 more than the ultimate stress of most tissues this does not change the conclusion that separation of membranes at tissue boundaries could occur. Overall then the conclusions of previous reports is unchanged. Damage to bulk tissues is unlikely but separation of membranes at organ boundaries is likely.

Modeling of Air Gun Bubble Dynamics

The modeling of the bubble produced by an air gun has its roots in earlier studies of underwater explosions. Two landmark papers in the field are [25, Ziolkowski, et. al., 1970] and [11, Landrø, 1992]. Recently there have been further refinements to the techniques used to calculate bubble dynamics [3, Cox, et. al., 2004]. The methods introduced in this latter reference are rather esoteric. This methods employed in our study are the earlier ones from [25, Ziolkowski, et. al., 1970] and [11, Landrø, 1992]. It would be possible, though a significant project, to revisit these calculations using the more recent methods.

The dynamics of an air bubble are modeled using a damped Kirkwood-Bethe equation

$$\ddot{R} = \frac{(1-u)H + (1-u)u\dot{H} - \frac{3}{2}(1-u/3)\dot{R}^2 - \alpha\dot{R}}{R(1-u)} \quad , \tag{7}$$

where R is the bubble radius, H is the enthalpy per unit mass of the water at the bubble wall, $u = \dot{R}/c$, c is the velocity of sound in water and α is an empirical damping coefficient. This is the equation of motion (i.e. Newton's 2nd Law) for the wall of the bubble. So the right side of the equation can be understood as a sum of forces acting on the bubble wall. The enthalpy per unit mass, H, can be found using an equation of state for water. In previous work the equation of state selected was the Tait equation

$$\frac{p(R)+B}{p_\infty + B} = \left(\frac{\rho}{\rho_\infty}\right)^\zeta \tag{8}$$

and this yields, via the usual definition of $H = \int dp/\rho$ an expression for H

$$H = \frac{\zeta(p_\infty + B)}{(\zeta - 1)\rho_\infty \left[\left(\frac{p(R)+B}{p_\infty+B}\right)^{(\zeta-1)/\zeta} - 1\right]} \quad , \tag{9}$$

where $B = 2500$ atm and $\zeta = 8$ are empirical constants, $p(R)$ is the pressure at the bubble wall, p_∞ is the "ambient" hydrostatic pressure at the depth of the bubble and ρ is the density of water. The pressure inside the bubble is not generally equal to the pressure of the water at the bubble wall because of surface tension and viscosity forces. But these can be shown [25, Ziolkowski, 1970] to be small. Treating the air in the bubble as an ideal gas and assuming adiabatic expansion of the bubble we get an expression for $p(R)$. This can be subject to relations allowing the mass of gas in the bubble to vary with time. This makes it possible to model bubbles due to multichamber air-guns. When all of these are combined the Kirkwood-Bette equation is converted to an ordinary differential equation in R. This can easily be integrated numerically using the standard fourth order Runge-Kutta algorithm or any other suitable numerical integrator. A typical result is shown in Figure 3.

Once the radius vs. time for a bubble has been found the pressure deviation at a distance r from the bubble can be found from

$$p_f(t) - p_\infty = \rho\frac{R(t')}{r}\left(H(t') + \frac{\dot{R}(t')^2}{2}\right) \tag{10}$$

where $t' = t - r/c$ is the "retarded time", which accounts for the travel time of a signal from the bubble to the location where $p_f(t)$ is being calculated. A typical example of a far field pressure is shown in Figure 4.

Calculations of Signals Due to Multiple Guns

If one assumes no interactions between bubbles then the pressure at some location can simply be calculated by summing the contributions due to each bubble. Further, reflection off of the surface can be handled by introducing "mirror images" of each bubble above the surface. This *method of images* is equivalent to modeling the water surface as a perfect reflector of sound. In this study we

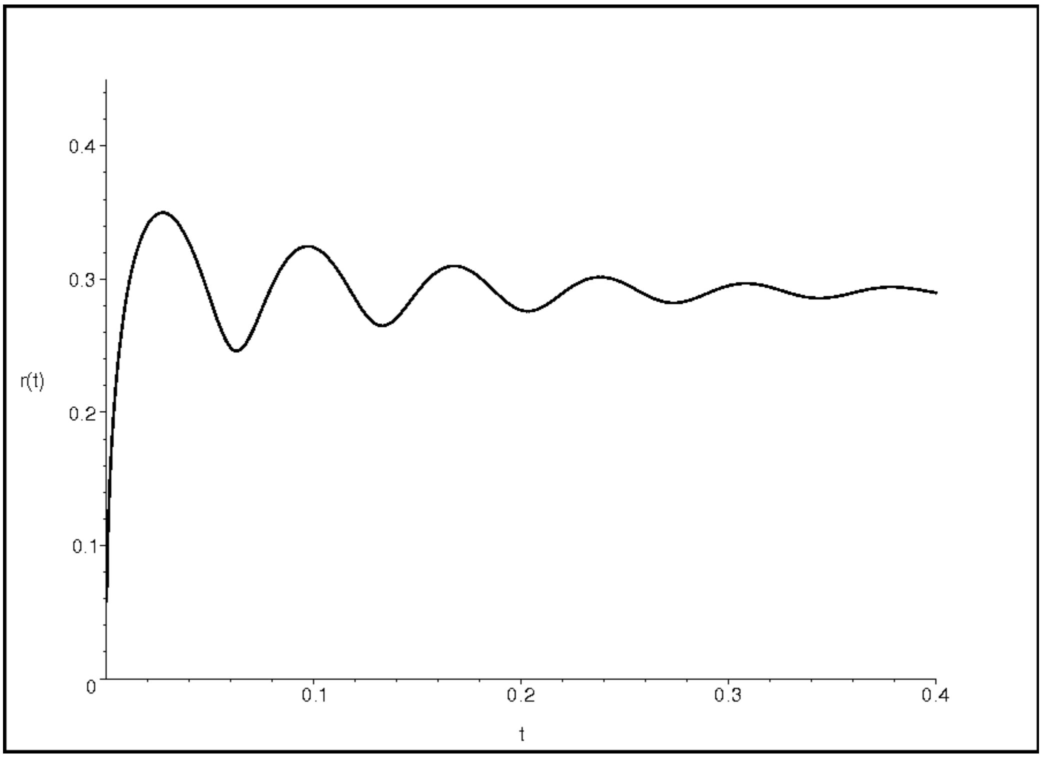

Figure 3: A typical radius vs. time for the bubble due to an airgun. This solution was found for a “GI” gun with 45 cu. in. generator chamber, 105 cu. in. injector chamber at a depth of 10 m.

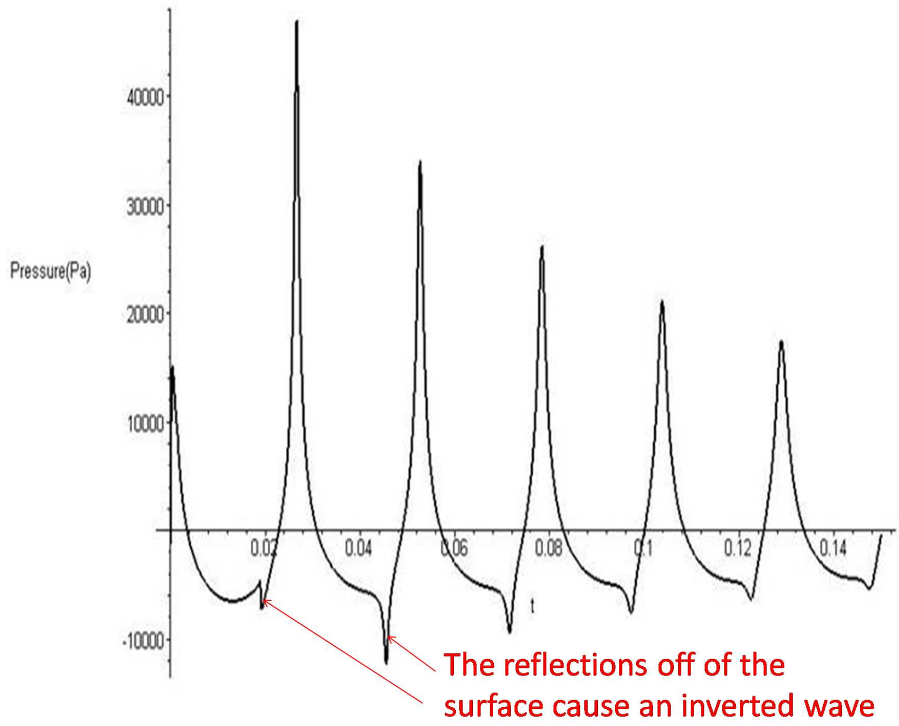

Figure 4: A typical pressure vs. time far from a bubble. This was found for a "GI" gun with 45 cu. in. generator chamber, 45 cu. in. injector chamber at a depth of 6 m and was calculated at a distance of 1 m from the air-gun. As noted, the effect of reflection off of the water surface was included in the calculation.

have restricted ourselves to this simple treatment of the surface reflection. More generally one could assume that the surface has a frequency dependent complex reflection coefficient (a surface impedance) and simply multiply the reflected signal by this. Models for appropriate impedances of water surfaces have been developed and depend on the roughness of the water surface. Including this in our model is well beyond the scope of this study.

A method for including interactions between sources was introduced in [26, Ziolkowski, et. al., 1982]. This, so-called *notional source method* was developed to allow the prediction of far-field sound signatures of arrays from near field measurements of individual gun signatures. However, the same idea can be applied to our predictions of individual air-gun signatures. The idea is to allow the "ambient" hydrostatic pressure at each gun be modified by sound arriving from other guns. Since the arrival of this sound is always delayed due to the transit time of the signals this causes no difficulty in numerically solving the Kirkwood-Bethe equation since the hydrostatic pressure at each gun depends on R(t) or other guns *at earlier times.* Having done this we get an R(t) for each gun that includes the interactions between the guns. These can now be treated as if they were isolated guns (notional sources) and we can sum the pressure deviations resulting from each normally. This has been carried out. As expected [26, Ziolkowski, et. al., 1982], it affects the low frequency part of the signature due to an array. Since the main concern with impacts of seismic shoots on crabs is the high frequency part of the incoming sound it is unlikely that this needs to be considered in future calculations of incident sound. However, our Maple sheets are now capable of handling it.

Constructing the Incident Sound Field at the Location of a Crab

Given an array of air-guns at arbitrary locations and a crab at some other location we are now able to construct the incident sound field outside the crab and produce the pattern of displacements inside the crab resulting from the multiple incident waves. Carrying this out for a significant sized array and over all frequencies is an enormously computationally intensive task and has not been carried out because of the short timelines of this project. However, we now have Maple sheets which can, in principle, carry out this calculation. A sample displacement vs. position plot is shown in Figure 2. This plot was mainly constructed as "proof of principle". It shows two waves passing through the tissues of a crab from separate air guns. Only two air guns were used and the waves were constructed from only two frequency components. This was done for two reasons. Firstly, it made the computation time short. Secondly, using more guns with more frequency components simply produces a plot which is a very complicated pattern of displacements and does not show clearly that the pattern results from multiple guns.

The actual process of constructing the incident sound field is quite involved and will only be sketched here. It involves a steady state approximation which could be removed in subsequent work.

1. The mode amplitudes of the sound inside the crab tissues and shell are found for a standard, unit amplitude, incident plane wave as described in [14, Lee-Dadswell, 2009].

2. The model array is constructed by defining the sizes and positions of the guns in it.

3. The $R(t)$ of each gun is computed, including interactions with all other guns.

4. The pressure, $p_f(t)$ is calculated for each "notional source" at a standard distance of 1 m.

5. The spectrum $\tilde{p_f}$ of each notional source is computed.

6. At the location of the crab the signal from each air gun is constructed by building a plane wave, directed along the line from the gun to the crab, using the notional source spectrum for the appropriate gun (this is the steady state approximation). The mode amplitudes at each frequency are rescaled by $1/r^2$ to account for the different distances to the guns.

7. The mode amplitudes of the sound inside the crab tissues and shell are rescaled according to the plane wave amplitudes for the incoming waves from each gun.

8. The displacement fields inside the crab due to each gun are rotated in the coordinate system so that they are oriented along the line from the gun to the crab.

9. The rotated displacement fields due to each gun are summed.

The steady state approximation could be removed in future work by calculating correct phase shifts for the plane wave components from each gun based on the travel time for the signals from the guns.

While the resulting calculations are rather long and involved, they yield results that are entirely consistent with the "quick and dirty" calculations of Wave Interference and the 255 dB "Typical Sound Level" above. The much simpler calculations of that section give us a worst case scenario which occurs along the line directly below the center of the array and at distances greater than the largest array dimension. The full calculations described in this section would allow one (at enormous computational expense) to find the sound intensities at any location (off the center line, or very near the array). This could allow one to establish what fraction of the seafloor under the array experiences sound levels over some threshold that one is interested in. However, it adds no new information about what the worst case sound levels are.