A Preliminary Theoretical Examination of the Absorbtion of Energy by Snow Crabs Exposed to Seismic Air-gun Pulses

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Executive Summary

A series of calculations have been carried out to determine whether seismic air-gun pulses used in marine oil exploration could cause physical damage to snow crabs. The focus of the study is largely on the energy delivered to and absorbed by the crabs since any tissue damage would have to be caused by absorption of energy leading either to excessive heating of the tissues or to tearing/crushing of the tissues.

The calculations summarized in this report model the seismic pulse as a plane wave of sound which should be a good approximation for seismic testing in relatively deep water. The model of the crab used is a standard one in acoustic scattering studies on crustaceans; the crab is modeled as an elastic sphere (the shell) filled with a liquid (the tissues). The calculation uses these simple models and classical theory of acoustics to arrive at estimates of the sound intensity inside the crab. This sound intensity value is then combined with estimates of the sound absorption characteristics and elastic properties of the crab's tissues to arrive at conclusions regarding the absorption of sound energy by a crab.

It is worth noting that sound propagation can be thought of as either pressure waves or as waves of particle displacement. These are complementary ways of viewing sound and either view ought to always lead to the same conclusions. This report makes use of both views with some emphasis on particle displacements. Two very different sound absorption mechanisms are examined in this report: viscous damping in the tissues and elastic failure (tearing or crushing) of the tissues. The estimates of thresholds of damage due to these two mechanisms suggest that:

1. Crabs may feel their internal organs vibrate as seismic pulses pass through them. Thus, crabs may respond and possibly experience stress as a result of seismic testing. More study would be needed to determine this.

2. No direct physical damage to snow crabs is expected to be caused by seismic pulses. The exception is that the separation of the outer membrane of the ovary reported in [1, Chadwick, 2004] might be directly caused by seismic pulses. This study cannot rule out the possibility that other organs might be particularly susceptible to damage. Further study would be needed to determine whether this is the case.

3. Over the course of this study significant progress has been made in developing a computer modeling application which can predict sound amplitude in the interior of a crab. This will be of use in future studies and could lead to a modeling package of use to other researchers, including but not limited to those investigating the effects of seismic air-gun pulses on invertebrates.

The present study was seriously hampered by the absence of data on the physical characteristics of crab tissues. It is recommended that experimental work be done to determine certain physical quantities of crab tissues. This will make it possible to better predict the effects of seismic pulses on crabs.

Introduction

Activities of the oil and gas industry have many potential impacts upon fisheries. One issue that is of concern is the potential impacts of carrying out seismic air-gun surveys. In a seismic survey a ship tows an array of airguns which is used to generate extremely loud pulses of sound which are used to map rock strata under the sea bottom. These sound pulses are sufficiently powerful (up to about 255 dB rel. 1 μPa [15, MacGillivray, 2005]) that there is concern over their effects on various marine organisms [1, Chadwick, 2004], [9, Goold, 1998], [17, Moriyasu, 2004]. Considerable work has been done to examine the effects of seismic test pulses on marine mammals (e.g. [9, Goold, 1998]). Work has also been done on the effects on fish. However, very little work has been done on the effects that seismic pulses might have on marine invertebrates. Of particular concern at the present time in Nova Scotia is the effect that siesmic surveys might have on snow crabs [17, Moriyasu, 2004].

The effects that might occur range from subtle behavioural and environmental changes which affect catchability, through immediate behavioural changes all the way to the possibility of direct physical damage to the crabs as a result of exposure to seismic test pulses [23, Walmsley, 2007]. The present study is only concerned with estimating the energy delivered to and absorbed by a crab exposed to seismic air-gun pulses. This allows us to make some first steps towards assessing the likelihood of the pulses causing direct physical damage to crabs. Previous experimental studies have been carried out [1, Chadwick, 2004],[17, Moriyasu, 2004] but they have been largely inconclusive. There are many possible reasons for this. Among them:

1. The sound levels that the crabs were subjected to may have been below the levels where physical damage ought to be expected.
2. There is insufficient knowledge of what physical damage ought to be expected or how such damage would be assessed.
3. Differences between test and control groups in [1, Chadwick, 2004] may have been caused by factors other than seismic pulses.

The present study aims to address the first of these issues. Knowledge of what sound levels might be expected to cause damage will allow future experimental studies to be better designed so that the experimenters know that they are within the regime where effects might be expected. In doing so we will be able to assess the likelihood that the minor differences between test and control groups in [1, Chadwick, 2004] were caused by exposure to seismic pulses. A significant constraint on the calculations in this study is that the experimental studies to date [17, Moriyasu, 2004] find little evidence for major physical damage to crustaceans due to seismic air-gun pulses.

Objectives

The experimental attempts to establish whether seismic testing has any impact on crabs and the crab fishery have been hampered by a lack of theoretical work on the subject. As a result, the experimenters have not understood what effects to look for or what threshold sound levels might cause those effects. The present study aims to develop the theoretical understanding necessary to guide future experiments examining the physical effects of seismic testing on crabs.

The proposal for this study set as a goal "to predict, at least within an order of magnitude, the fraction of energy incident upon a snow crab that is absorbed" by the body mass of a crab. This goal has been achieved, although the lack of experimental values for the material properties of crab tissues makes it hard to judge whether the estimate is within an order of magnitude. However, this study is able to conclude with some confidence that the intensity of sound due to a seismic pulse is several orders of magnitude too low to cause direct physical damage to a crab.

The proposal also stated that the project might yield "a summary of the state of knowledge of the relevant material properties of the carapace and soft tissues of the crabs." This has turned out to be a larger issue in this study than was initially expected and a very large portion of this report is devoted to summarizing the (scanty) existing knowledge of the material properties of crab tissues and carapace. Additionally, significant effort has gone into making estimates of these properties where they are not known. This work has gone considerably beyond what was predicted in the original proposal.

A calculation has been carried out to estimate the minimum sound levels that might be expected to cause physical damage to crabs. In a study of such limited scope with so little previous work done on the subject it is only possible to make a very rough estimate. However, the estimate arrived at will be useful as a starting point for future studies. Additionally, this study should help to establish what areas require further work.

Approach

An initial literature search was carried out with assistance from an undergraduate research assistant, Matthew Moy. Additionally, a trip to St. Francis Xavier University to visit with Dr. Edwin DeMont yielded a very useful list of sources and some additional useful advice on what should be considered in the calculation.

To determine the amount of energy absorbed by the crab during exposure to a seismic pulse we need to know the sound intensity inside the crab. In the frequency range that dominates sound from an air-gun array the sound intensity inside the crab should be very similar to the intensity outside the crab. A more detailed calculation can be done to get a better estimate of the sound intensity inside the crab. An undergraduate research assistant, Jonathan Ettinger, was hired to assist with the calculation and the calculation has been carried out (see Annex).

The sound intensity calculation uses approaches from classical acoustics. The incoming sound wave is approximated as a plane wave (the approximation is valid far from the source - i.e. in deep water). Individual frequency components of the pulse are treated separately. The crab is treated as an elastic sphere (approximating the shell) filled with a liquid (approximating the tissues). In the classical acoustics approach we now write down expressions which describe the sound outside the crab, within the shell, and inside the crab. We then write down the conditions conditions which must be met at the water-shell boundary and at the shell-tissue boundary. This yields a set of equations which can be solved to determine the sound intensity inside the crab. This approach was taken with help from Jonathan Ettinger. The actual solution of the equations was carried out with the software package, Maple. Much of the Maple coding was done by Jonathan Ettinger. The calculation confirms that the sound intensity inside the crab is approximately the same as that outside the crab.

Knowing the sound intensity inside the crab we can examine two dominant processes of sound absorption: viscous damping and elastic failure. This would be easily done once we know the sound intensity inside the crab if we knew the sound propagation and damping characteristics of crab tissues. Unfortunately, this data is not available in the literature. As a result, the acoustic and mechanical characteristics of the crab tissues have had to be estimated. This was a far larger part of the research than was envisioned. The process of estimation is summarized in the Findings and the Annexes below.

Findings

To be able to make reliable theoretical predictions of the effects of high intensity sounds on crabs we need to know about the sound propagation and absorption characteristics of crab tissues and the chitin in crab shells. There exists a considerable body of work on sound propagation in tissues [3, Duck, 1990]. Unfortunately, almost all of this work has been driven by clinical research and so it been done for sound at ultrasound frequencies and only on mammalian tissues. We must, therefore, try to estimate the speed of sound in crab tissues and the damping coefficients. This is the largest source of uncertainty in the findings of this study. Experiments to determine the sound propagation and damping characteristics of crab tissues could be easily carried out. This would allow considerably more confidence in estimates of what sound levels might be dangerous. For the present study these numbers have been estimated via various means which are described in the Annexes. The most relevant conclusions are as follows:

1. Transverse waves are poorly transmitted into and through soft tissues; to a reasonable approximation, the tissues can be treated as a liquid for the purposes of these calculations.

2. At the frequencies present in a seismic pulse, viscous damping of longitudinal (compression) waves in tissues is very weak. A compression wave can travel through kilometers of tissue with very little damping. To determine the manner of sound propagation through the tissues we can ignore damping.

The initial calculations to establish the validity of the model also yield some useful results immediately. The total sound energy delivered to a typically sized crab for sound at a level of 255 dB rel. 1 μPa (about the highest sound level to be expected in a seismic test pulse) is about 10 kJ. As mentioned above, viscous damping by tissues is very weak. Only about one one-hundred thousandth to ten millionths of the sound energy incident on the crab could be absorbed due to viscous damping. As a result, the maximum temperature increase of a crab due to this mechanism is a tiny fraction of a degree. Such a tiny amount of heating is of no concern.

Having established that we can ignore transverse waves (i.e. treat the tissues as a liquid) and ignore viscous damping we are able to carry out the calculation which predicts the sound intensity at all points within the crab. We find very little focusing of sound waves within the crab (see Figure 1). Thus, sound levels within the crab are not significantly higher than outside the crab at any point (and at most frequencies the sound levels are somewhat lower inside the crab than they are outside). We are able to find the size of particle displacements inside the crab. The maximum particle displacements are much less than the elastic limits of the tissues.

The most detailed experimental study of physical damage to snow crabs by seismic pulses is found in [1, Chadwick, 2004]. Various minor differences be-

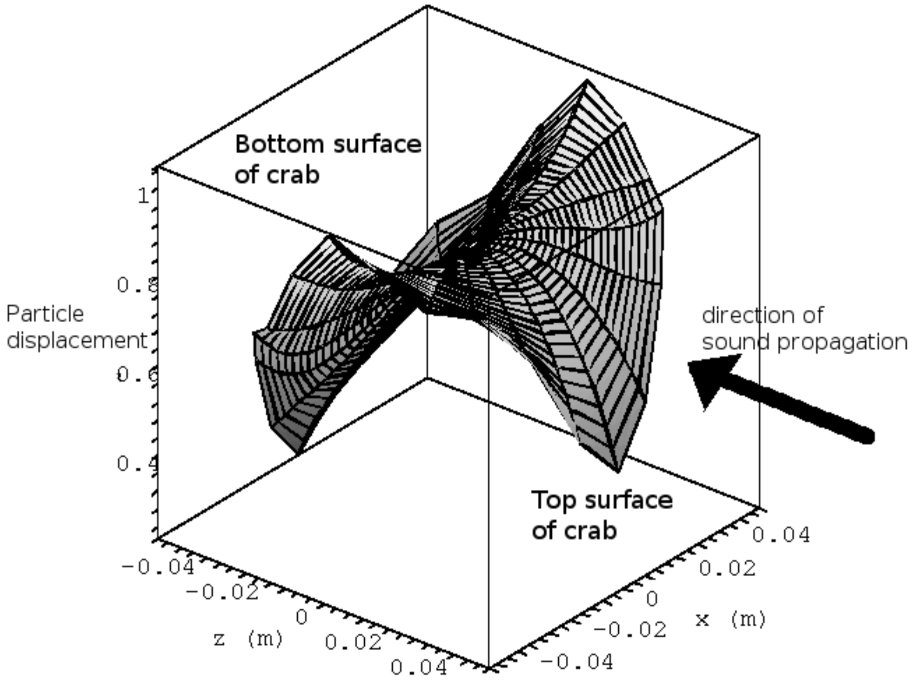

Figure 1: Magnitude, $|\psi|$, of the displacement potential inside a 10 cm radius crab for sound with a frequency of 10000 Hz. The view shows a vertical cross section through middle of the crab with up (the direction that the sound is coming from) roughly to the right in the figure. The vertical scale is set so that 1.0 indicates the sound amplitude outside the crab. As can be seen, the sound amplitude is lower everywhere inside the crab than it is outside the crab.

tween the test and control groups were reported in this study. These differences included bruising of some tissues and separation of the outer membrane from the ovaries. However, the authors pointed out that most of these differences could have been caused by stress response or other factors. In light of the above results it seems likely that the bruising of tissues was caused by factors (perhaps including stress response of the animals) other than direct physical damage by the sound pulse. While the particle displacements calculated in the present study are too small to cause tissues to exceed their elastic limits it is plausible that they might cause the separation of ovary membranes reported in [1, Chadwick, 2004]. The strain required to separate one tissue from another is typically small than the strain required to cause damage to an organ. However, more study would be needed to determine whether this is actually occuring.

Although the particle displacements occuring in the crabs are too small to directly damage tissues, they are large enough that it is highly plausible that the crabs can feel them. Thus, short term behavioural responses (including stress response) could be induced in the crabs. Once again, more study would be necessary to establish whether this is happenning.

Recommendations and Conclusions

The overall conclusion of this study is that direct physical damage to tissues of snow crabs by seismic pulses is unlikely. The amount of energy deposited in the crab through viscous damping in the crab's tissues is negligible and the particle displacements experienced within the crab's tissues are below the elastic limits of the tissues. This conclusion remains true even for the highest sound intensity levels that are expected to be experienced by the crabs. Thus, the minor effects reported in [1, Chadwick, 2004] are most likely a result of the stress responses of the crabs or other confounding factors. The exception may be the separation of the outer membrane of the ovaries in the crabs. More study is would be needed to determine whether this effect was directly caused by the seismic pulses.

The particle displacements experienced by the crab are large enough that the crabs can almost certainly feel them. The crabs ought to exhibit immediate behavioural responses to seismic pulses. More study would be needed to establish this.

The present study has been seriously hampered by the lack of data on the physical characteristics of the tissues and cuticle of crabs. Thus, all of the above conclusions cannot be made with full confidence. It would be relatively easy to determine key physical characteristics of the crab's tissues experimentally. The physical characteristics most needed are:

1. Speed of sound in crab cuticle (and seasonal variation of this value).
2. Shear and bulk viscosity of various representative crab tissues.
3. Speed of transverse waves through various representative crab tissues.
4. Elastic limits (especially yield point) of various representative crab tissues.

It is recommended that a study be carried out to determine these and that the experimental values be compared with the estimates contained in this report.

A large amount of theoretical work still needs to be carried out. Once better data is available for tissue properties most of the calculations carried out in this report need to be revisited. Additionally, the main calculation in this report should be improved in the following ways:

1. Does the presence of the sea bottom just under the crab have a significant effect on the sound levels inside the crab? The calculation in this report should be repeated including effects of reflection from the bottom.
2. The calculation should be modified to include shear waves in the tissues to verify or refute the assumption (made in this report) that shear waves are poorly transmitted into the tissues.
3. The crab would be better modeled as an oblate ellipsoid (flattened sphere). This calculation should be repeated with the crab modeled in this way. This will considerably increase the complexity of the calculation but, in principle, the calculation can be carried out in the same way.

4. Including the effects of damping in the tissues in the calculation will improve the confidence of the conclusions. This can only be done once the experimental work has been done to determine the most important sound propagation properties of the tissues.

5. A calculation similar to the one in this report should be carried out to examine the possibility of damage to crab larvae swimming in the water column.

   The Maple code produced in the present study to calculate the sound intensity inside a crab should be a valuable resource in further studies. Additionally, it can be further modified to incorporate all of the above recommendations for improvements to the calculation. In the long run this package could be developed into a simulation application which could be of use in modeling of interactions between sounds and a wide variety of objects. This could have application well outside of the study of the impacts of air-gun noise on crabs if it is properly developed. It is recommended that further development of this package be carried out as part of the work recommended above.

References

[1] Michael Chadwick. Potential impacts of seismic energy on snow crabs. Habitat Status Report 2004/003, Canadian Department of Fisheries and Oceans, 2004.

> This report is currently the best existing experimental study of the effects of seismic testing on snow crabs. It summarizes the results of a study in which crabs were placed in cages on the seabottom in the area of an actual seismic shoot. A control group was placed in cages elsewhere. The study is highly inconclusive. Very few differences were observed between the experiment and control groups. As the authors point out, the differences that are observed could have been caused by factors other than the seismic sound (handling, differences in the environment experienced by the experiment and control groups, etc.).

[2] Clarence S. Clay and John K. Horne. Acoustic models of fish: the Atlantic cod (Gadus morhua). *Journal of the acoustical society of America*, 96:1661–1668, 1994.

[3] Francis A. Duck. *Physical Properties of Tissue: A comprehensive reference book*. Academic Press, London, 1990.

> This is a comprehensive book containing a summary of what was known of the physical properties of tissue at the time it was written. The primary audience is medical researchers and so there is a heavy focus on human and other mammalian tissues. What information there is on sound propagation in tissues is almost entirely restricted to behaviour at ultrasound frequencies. Nevertheless, it serves as a useful jumping off point. It includes chapters on thermal properties, optical properties, acoustic properties, mechanical properties, electrical properties, interactions between ionizing radiation and tissues, nuclear magnetic properties and tissue composition.

[4] C. Feuillade and R. W. Nero. A viscous-elastic swimbladder model for describing enhanced-frequency resonance scattering from fish. *Journal of the acoustical society of America*, 103:3245–3255, 1998.

[5] Lawrence Flax and Werner G. Neubauer. Acoustic reflection from layered elastic absorptive cylinders. *Journal of the acoustical society of America*, 61:307–312, 1977.

[6] Ralph R. Goodman and Raya Stern. Reflection and transmission of sound by elastic spherical shells. *Journal of the acoustical society of America*, 34:338–344, 1962.

[7] Takahi Hasegawa, Yasutaka Hino, Akio Annou, Hideki Noda, and Masahiko Kato. Acoustic radiation pressure acting on spherical and cylindrical shells. *Journal of the acoustical society of America*, 93:154–161, 1993.

[8] Takahi Hasegawa and Yumiko Watanabe. Acoustic radiation pressure on and absorbing sphere. *Journal of the acoustical society of America*, 63:1733–1737, 19778.

[9] Peter J. Fish John C. Goold. Broadband spectra of seismic survey air-gun emissions, with reference to dolphin auditory thresholds. *Journal of the acoustical society of America*, 103:2177–2184, 1998.

> This paper contains several spectra of air-gun noise taken at various (quite long) distances from the air-gun array. It is useful for getting a general idea of what the frequency range for air-guns.

[10] L. D. Landau and E. M. Lifshitz. *Theory of Elasticity*. Pergamon Press, Oxford, second edition, 1970.

> This is the standard text on theory of elastic materials. It is a classic, known to many physicists.

[11] L. P. Lebedeva. Measurement of the dynamic complex shear modulus of animal tissues. *Soviet physics – acoustics*, 11:163–165, 1965.

[12] F. Léon, F. Chati, and J. M. Conoir. Acoustic scattering by an elastic elliptic cylinder in water: numerical results and experiments. *Ultrasonics*, 42:297–300, 2004.

[13] Richard H. Love. Resonant acoustic scattering by swimbladder-bearing fish. *Journal of the acoustical society of America*, 64:571–580, 1978.

[14] Xavier Lurton. *An introduction to underwater acoustics: principles and applications*. Springer, Berlin, 2002.

> This text is mostly directed at engineers, particularly those interested in underwater remote sensing. It has a good discussion of sound absorption by water in the second chapter.

[15] Alexander O. MacGillivray and N. Ross Chapman. Results from an acoustic modelling study of seismic airgun survey noise in queen charlotte basin. Technical report, BC Offshore Oil and Gas Team, 2005.

[16] Stefan Machlup. A theoretical model for sound scattering by marine crustaceans. *Journal of the acoustical society of America*, 24:290–293, 1952.

[17] M. Moriyasu, R. Allain, K. Benhalima, and R. Clayton. Effects of seismic and marine noise on invertebrates: A literature review. Research Document 2004/126, Canadian Science Advisory Secretariat, 2004.

This is currently the most comprehensive list of sources directly relevant to the study of seismic effects on invertebrates. It is focused on experimental studies. The summaries of the papers presented in this collection serves as very useful background information on sound levels from various sources and the effects that have been observed.

[18] Arthur N. Popper, Michele B. Halvorsen, Andrew Kane, Diane L. Miller, Michael E. Smith, Jiakun Song, Peter Stein, and Lidia E. Wysocki. The effects of high-intensity, low-frequency active sonar on rainbow trout. *Journal of the acoustical society of America*, 122:623–635, 2007.

[19] D. Raabe, C. Sachs, and P. Romano. The crustacean exoskeleton as an example of a structurally and mechanically graded biological nanocomposite material. *Acta Materialia*, 53:4281–4292, 2005.

[20] C. Sachs, H. Fabritius, and D. Raabe. Experimental investigation of the elastic-plastic deformation of mineralized lobster cuticle by digital correlation. *Journal of Structural Biology*, 155:409–425, 2006.

[21] T. K. Stanton. Sound scattering by spherical and elongated shelled bodies. *Journal of the acoustical society of America*, 88:1619–1633, 1990.

[22] Timothy K. Stanton, Dezhang Chu, Peter H. Wiebe, Robert L. Eastwood, and Joseph D. Warren. Acoustic scattering by benthic and planktonic shelled animals. *Journal of the acoustical society of America*, 108:535–550, 2000.

[23] R. D. Walmsley. Proceedings of a workshop on research priorities: The impacts of seismic exploration activities on marine invertebrates. Technical report, OEER Association, 2007.

Annexes

Summary of Approach and Assumptions Made

The details of the interaction between a seismic test pulse and a crab are highly complex. Nevertheless, at a fundamental level the question of whether a seismic test pulse will cause physical damage to a crab comes down to a relatively simple question: how much energy is delivered to the crab by the pulse and how much of that energy is absorbed?

The first part of this question is primarily an issue of what the sound level is at the location of the crab (i.e. at the bottom). This turns out to be a rather complicated question because the sound levels at the bottom depend on the characteristics of the seismic airgun array, location on the bottom relative to the array, depth of the water, temperature profile, and other factors. However, much previous work has been done on this (e.g. [15, MacGillivray, 2005] and [9, Goold, 1998]). The present study will treat the sound level on the bottom as a known parameter. The maximum sound levels reported for seismic pulses is variously reported (e.g. [15, MacGillivray, 2005]) as around 255 dB rel. 1 μPa. This sound level will be used as the "worst case" throughout this study. It should be noted that sound levels above about 255 dB are highly unlikely to occur. If the pressure amplitude of the sound waves exceeds the ambient pressure of the fluid then the low pressure regions due to the sound waves will be vacuum. This is called cavitation. It results in rapid damping of the sound wave. Even the 255 dB level quoted above is only possible at a rather large depth below the surface of the water where the ambient pressure is higher than atmospheric.

The second part of the question is considerably more difficult to answer and very little has been done to answer it. First we must understand what the mechanisms of sound absorption in the crab are. The following are the most likely mechanisms:

1. Absorption of the sound wave due to viscous damping in the crab's tissues.
2. Crab tissues reaching their elastic limit as a result of particle displacements caused by the sound wave.
3. Damage caused by the initial shock wave from the seismic pulse (rupture caused by a large pressure gradient).

Mechanism 3. is almost certainly only a concern at very short distances from the airgun array (i.e. in very shallow water). This is an area that is worth investigating but is beyond the scope of the current study for two reasons. First of all, most seismic testing takes place in deeper water where this is not a concern. Secondly, the dynamics of shock waves is a highly complicated and somewhat poorly understood area of study. The author of the present report is not qualified to examine effects of shock waves.

Mechanism 2. could also be seen as an effect of pressure gradients. A propagating sound wave can be viewed in two equivalent ways: as a propagating pattern of high and low pressure regions, or as a propagating pattern of particle displacements. Viewed in the first way, damage to tissues would be caused by the forces arising from the pressure gradients exceeding the strength of the tissues. Viewed in the second way damage is thought of as resulting from the tissue being stretched or compressed beyond the maximum deformation that it can tolerate. Up to the elastic limit the amount of deformation (the size of the particle displacements) is proportional to the force. So these two approaches are equivalent. Damage will begin to occur when the elastic limit is reached, so for our present purposes it is sufficient simply to establish whether the elastic limit is reached.

Mechanism 1. leads to heating of the crab as the sound energy of the pulse is converted to thermal energy by internal friction in the crab's tissues. If the heating were sufficient, this could kill or injure the crab. However, as will be seen, dangerous heating of the crab is not a likely outcome of any realistic seismic test pulse.

We must first know what the sound levels are inside the crab given a known sound level outside the crab. We adopt a simple model for the sound wave and for the crab. Some preliminary calculations help to establish the validity of the simple model. The model allows us to solve the equations describing the propagation of the sound waves. Having done this we can determine the sound intensity at all locations inside the crab. Knowing this we can determine the rate of energy absorption via mechanism 1. and can determine the particle displacement at all locations in the crab to establish whether the elastic limit is reached.

A major issue throughout this study has been the unavailability of experimental values for physical characteristics of crab tissues. We need to know all of the physical characteristics necessary to determine the speed of sound in the crab's tissues and the damping coefficients. We also need to know the elastic limit of the crab tissues. Such information is not in the literature – at least not in any form that can be easily found. Thus, a significant portion of the Annexes of this report deal with the manner in which these physical characteristics have been estimated. The uncertainty in the final conclusions of the report is largely due to our lack of knowledge about basic physical characteristics of crab tissues.

Source and target characteristics

A seismic airgun array produces a short burst of sound which propagates downward through the water column. The array is designed to take advantage of interference effects between the individual airguns. As a result, sound is quite focused downwards in a "beam". The intensity of sound in this beam falls off much more slowly than the usual inverse square relationship for point sources of sound. Additionally, the far field sound is enhanced by coherence between the signals from the individual airguns in the array. The current study is not intended to closely examine the sound field produced on the bottom. Such work has been done[15, MacGillivray, 2005] and the model of the seismic signal at the bottom used in this report is based on these studies. The details of a pulse depend on angle from vertical under the array (azimuthal angle), water depth, temperature profile and numerous other factors. The bulk of the sound energy in the seismic pulse is at frequencies between 100 and 300 Hz, however there is a significant sound level up to frequencies in the 30 000 Hz range [9, Goold, 1998]. The duration of the pulse is on the order of 100 ms [9, Goold, 1998]. Of great interest is the sound level. Source sound intensity levels for airgun arrays are quoted to be as high as 255 dB rel. 1 μPa in the near field. Far field levels, which are of more interest in this study are difficult to estimate as they can be highly dependent on azimuthal angle, water depth and temperature profile. But directly under the array can be comparable to or even larger than the near field levels due to coherence effects. The calculations in this study examine the effects of sound intensity levels up to 255 dB relative to 1 μPa. For the present study a very simplified picture of the pulse will be adopted. We will treat the seismic pulse as a plane wave of uniform sound intensity which lasts for 100 ms. At various times we will adopt various "worst case" scenarios in terms of the frequency spectrum of the pulse. These scenarios will be described as they are used.

The "target" is taken to be an adult snow crab. For the present study we adopt the same model of a crab as was used in [16, Machlup, 1952]. In that paper marine crustaceans are modeled as a spherical, thin elastic shell filled with a nonviscous liquid. This makes analytical calculations tractable. Two major objections arise immediately:

1. A crab is not spherical: The scattering of sound by an object depends on the details of the object's shape. However, the fraction of sound scattered vs. transmitted only depends weakly on the shape of the object. The present study is only concerned with an order of magnitude estimate of this. Thus, the fine details of the effects of the crab's shape are not important and a spherical model will be adequate.
2. The interior of the crab is not a uniform, nonviscous liquid: Of particular concern in this study is the degree of sound absorption by the interior of the crab. However, at the frequencies examined (less than 30 kHz) the absorption of sound by tissues is weak, as will be seen below. So for determining how much of the sound is reflected, how much is transmitted through the shell and what the sound intensity is at various points inside the crab it will not be necessary to include the effects of the viscosity of the crab's interior. Additionally, shear waves do not transmit well through tissues [11, Lebedeva, 1965] and so it is reasonable to treat the tissues as a liquid, at least in this preliminary study. This will be discussed in greater detail below. The effects of the interior structure (organs) of the crab will be small since the differences in sound propagation speed through them are small [3, Duck, 1990].

A major issue in this study has been aquiring information on sound propagation characteristics of the shell and internal tissues of a crab. Very little data is available on this. The best that can be done without further study is to make estimates based on properties of other tissues such as those found in [3, Duck, 1990]. This will be discussed in more detail below.

Sound propagation in tissues and chitin

Speed of sound

No source was found which gives the speed of sound in any crab tissue. No doubt the speed of sound differs from one tissue to another, as in other animals. However, as in other animals the speed of sound probably does not differ by very much between tissues. Across species and across tissue types, a typical speed of sound is 1600 m/s [3, Duck, 1990]. This value will be used throughout this report as an estimate of the average speed of sound through crab tissues.

The speed of longitudinal (shear) waves in tissues is also needed to justify the model adopted. Very little was found in the literature on longitudinal waves in tissues, probably because tissues are such poor transmitters of longitudinal waves. A study by Lebedeva [11, Lebedeva, 1965] gives values for the shear moduli of various fish muscles of $\mu_0 = 0.1 \times 10^6\, dyn/cm^2$ to $5 \times 10^6\, dyn/cm^2$. Adopting approximately the middle of this range, $1 \times 10^6\, dyn/cm^2$, and using a tissue density of 1000 kg/m^3 we use

$$c_t = \sqrt{\frac{\mu_0}{\rho}} = 10\, m/s. \tag{1}$$

This is in agreement with [3, Duck, 1990] which gives c_t as lying in the range from 9-100 m/s. The value for the speed of transverse waves in tissues is, therefore, very low. Chitin, being much stiffer, should have a much higher speed for transverse waves. The large difference in sound speeds means that sound will mostly reflect off of the interface between chitin and tissue. Additionally, the wavelengths of transverse waves in the tissue will be very long compared to the size of the crab. Hence, there will be no standing transverse waves generated in the tissues. Under these conditions transmission of transverse waves into the tissue is expected to be very weak. Hence, it is reasonable to treat the tissues as a liquid, in which no transverse waves are possible.

The sound speed in the crab shell can be found from its elastic modulus. What we actually need to find the speed of sound is the bulk modulus but the only moduli that seem to be reported in the literature for crustacean cuticle are the Young's modulus and shear modulus. However, the various elastic moduli of a material are generally of the same order of magnitude. This may not be true of crustacean cuticle material which is a highly complex nanocomposite material. But in the absence of reported values for the bulk modulus this assumption will have to do. The elastic moduli of various crustacean cuticle materials are variously reported to be in the range of 3-9 GPa [20, Sachs, 2006],[19, Raabe, 2005]. This value will vary seasonally. Additionally it will vary from one part of the crab shell to another since some parts of shell are more mineralized than others. For present purposes we will use an estimate of 5 GPa but note that it could likely be as much as twice this or as little as half of this. Using this value with $c = \sqrt{(\mu/\rho)}$ we obtain a speed of sound in the crab shell of approximately 2000 m/s, which is certainly a reasonable value for a material of this stiffness. Since we do not know both the bulk and shear moduli we will need to use this value for the speeds of both longitudinal and shear waves. In all likelihood the speed for shear waves is somewhat lower than that for longitudinal waves, but not by a large factor.

Sound damping

Chitin is quite rigid and so there should be relatively little sound damping in it. Additionally, the shell of a crab is sufficiently thin that any damping that did occur in the crab's shell would have a minimal effect on the sound intensity inside the crab. Finally, damage to the crab due to viscous damping in the shell is not anticipated to be of any concern. For all of these reasons it is reasonable to treat the crab shell as an elastic (i.e. non damping) solid medium.

The damping of sound in the tissues is small enough as to have little effect on the sound intensity. So all damping will be ignored in the sound intensity calculation. However, to justify this, and to estimate how much energy is deposited in the tissues due to viscous damping, we do need to know the damping characteristics of the crab tissues. Because we are ignoring transverse (shear) waves we are not concerned with damping coefficients for them. We can obtain an estimate of the damping coefficient for longitudinal (compression) waves from the standard hydrodynamic relationship [10, Landau, 1970]

$$\gamma_u = \frac{\omega^2}{2c_\ell^3\rho}\left[\frac{4}{3}\eta - \zeta + \frac{\kappa T\alpha^2\rho^2}{C_P^2}\left(1 - \frac{4}{3}\frac{c_\ell^2}{c_t^2}\right)^2\right] \tag{2}$$

in which ω is the angular frequency of the sound, c_ℓ is the speed of sound (longitudinal waves), ρ is the fluid density, η is the shear viscosity, ζ is the bulk viscosity, κ is the thermal conductivity, T is the temperature in Kelvins, α is the thermal expansion coefficient, C_P is the constant pressure specific heat capacity per unit volume, and c_t is the speed of transverse waves. For an incompressible fluid the bulk viscosity, ζ, can be ignored (this is called Stokes' assumption) so we will do so. The values of c_ℓ and c_t were found above. The shear viscosity presents a problem since very little work seems to have been done to determine it for any tissues. In [11, Lebedeva, 1965] the loss factor due to shear is found in the 1-10 kHz range of frequency. From this we can estimate the shear modulus of an animal tissue to be of the order of magnitude of 1 $kg \cdot m^{-1} \cdot s^{-1}$. However, it is likely quite frequency dependent and probably varies widely from one tissue to another. This estimate may not even be good to within an order of magnitude. The remaining physical constants are less difficult to obtain and were found in [3, Duck, 1990]. The values quoted in this reference are generally for mammalian tissues and so we should be dubious of applying them to a crustacean. The thermal conductivities of most tissues are in the range of 0.5 $W \cdot m^{-1} \cdot K^{-1}$. The specific heat capacities of tissues are generally in the range of 3×10^6 $J \cdot K^{-1} \cdot m^{-3}$. Thermal expansion coefficients of tissues are typically about $5 \times 10^{-4}\ K^{-1}$. All of these values vary considerably from one tissue to another but rarely by more than a factor of. In any case the term in (2) involving the shear viscosity dominates so our uncertainty in κ, C_P and α does not matter. However, our uncertainty about η is a major problem. Combining all of these values we obtain a value for the damping coefficient of about $6 \times 10^{-6}\ m^{-1}$. This is *extremely* weak damping. In fact at first sight it is rather difficult to believe since this damping constant indicates that a sound in the 1 kHz range travelling through tissue will damp to half of its original intensity over a distance of several thousand kilometers! However, we can check how reasonable the value is in a number of ways. First of all, the damping coefficient ought to be higher than that of water. The comparable value for seawater at these frequencies is about one tenth this ($1 \times 10^{-7}\ m^{-1}$) or less [14, Lurton, 2002]. At ultrasound frequencies (about 1 MHz) the value is in the range of 0.001 m^{-1}. In the ultrasound frequency band the damping coefficient is seen to vary approximately linearly with frequency [3, Duck, 1990]. Extrapolating this dependence of γ_u with frequency to the kHz range that we are interested in we obtain an estimate for η of $1 \times 10^{-5}\ m^{-1}$. In light of this the result reported above is actually quite believable. The validity of these extrapolations is highly doubtful since there are certainly molecular relaxation mechanisms that we are ignoring. But in the complete absence of experimental results for the tissues of interest in the frequency range that we need this is the best we can do.

The Elastic Limit of Tissues

When a material is stretched or compressed we characterize its behaviour in terms of the stress (applied force per unit area) and the strain (distance that the material is deformed per unit length of material). For small deformations the strain is proportional to the stress. This is called elastic behaviour. At some value of the stress (the yield point) the relationship ceases to be linear. Most often this results in more deformation per unit of applied force as the material undergoes irreversible deformation. At some higher value of the stress (the ultimate stress) the material breaks. This breaking point is often characterized by a maximum fractional strain which is the maximum deformation per unit length of the material. While this behaviour is characteristic of many materials, many materials – including muscle – behave very differently.

Values of maximum fractional strain are available for many tissues [3, Duck, 1990]. As usual these are usually for mammalian tissues (in this case almost entirely for human tissues). However, very broadly, brittle tissues such as nerves, tendons and cartilage have maximum fractional strains of about 0.2 (in other words, the tissues snap when they are elongated by 20% of their original length). However, damage to a tissue occurs will before the maximum fractional strain. Damage will occur when the yield point is reached. No data is available on yield points of tissues, but fairly typically the yield point is at a half to a third of the maximum fractional strain. Taking the smaller (more pessimistic) value of one-third of the maximum fractional strain we arrive at a fractional strain threshold for damage of 7%. We will adopt this as a somewhat pessimistic value to use for all tissues in the crab.

Amount of Energy Delivered to a Snow Crab by a Seismic Pulse

The amount of energy arriving at the surface of the snow crab due to a seismic pulse is very easily estimated. If we assume a sound intensity level due to the pulse of 255 dB rel. 1 μPa then the pressure amplitude of the pulse is found from

$$\beta = 20 \log \left(\frac{\Delta P}{\Delta P_0} \right) \tag{3}$$

where β is the sound intensity level, ΔP is the pressure amplitude of the pulse and $\Delta P_0 = 1$ μPa is the reference level. This gives a pressure amplitude for 255 dB sound of 5.6×10^6 Pa. This yields the sound intensity from

$$I = \frac{\Delta P^2}{2\rho c} \tag{4}$$

which for 255 dB sound in water gives a sound intensity of $1X10^7$ W/m^2. Assuming a crab about 10 cm across and a pulse duration of 100 ms this gives a total energy incident on the crab of 10 kJ.

Absorption via Viscous Damping

As estimated above, the damping coefficient for sound in the 1 kHz range passing through tissue is approximately 1×10^{-6} m^{-1}. If a pulse of total energy E_0 passes through tissue for a distance d then that amount of energy absorbed is approximately

$$E_{abs} \approx \gamma_u d E_0 / 2 \tag{5}$$

where the approximation is valid for d much less than $1/\gamma_u$, which is certainly true for sound passing through a crab. Using 10 kJ as E_0, a thickess of crab of $d = 5$ cm and γ_u from above we arrive at a total absorbed energy (due to viscous damping) of 2.5×10^{-4} J. This is a very small quantity of energy. Using a specific heat capacity per unit mass of $C_P = 3 \times 10^3$ $J \cdot kg^{-1} \cdot K^{-1}$ and a mass for a crab of 1 kg we conclude that this absorbed energy would raise the body temperature of the crab by $8 \times 10^{-8\circ}$ C. This is certainly of no concern.

Several comments are necessary on the reliability of the above estimate. The sound damping coefficient is highly uncertain. It is certainly no lower than 1×10^7 m^{-1} (the value for seawater). It is likely to be as high as 1×10^5 m^{-1} (the value obtained by simple extrapolation from values known for ultrasound). If there are major molecular relaxation modes that contribute it could be even higher than this. However, this value was estimated for sound at 1 kHz. So in the above estimate we have approximated the seismic pulse as being entirely composed of sound at 1 kHz. There is a small portion of the spectrum of a seismic pulse in the range of 10 kHz. At these frequencies the absorption will be about 10 times stronger than what was estimated above. However, the bulk of the energy in the seismic pulse is in the 100-300 Hz range. At these frequencies the damping is likely 10 times weaker than the above estimate. So, in all likelihood, the above estimate is pessimistic and the energy absorbed due to this mechanism is less than the above estimate. The conclusion is certainly that heating of the crab due to viscous damping of sound in its tissues is not a concern.

Simple Calculation of Particle Displacements Within the Crab

Before carrying out the more complicated calculation to find the particle displacements inside the crab we can arrive at a very simple estimate of the maximum particle displacements within the crab. We will assume no reflection of the waves by the shell. This will overestimate the sound intensity inside the crab. We will also ignore refraction of the waves as they pass from the water into the crab. This will tend to underestimate the sound intensity at points in the crab where the waves are focused. The extent to which these effects are important can only be determined once we do the full calculation below. But this will give us an order of magnitude estimate that will be useful for comparison with the full results and will guide what effects we look for in the results of the full calculation.

Under the above set of assumptions the pressure amplitude of the waves inside the crab is the same as that outside the crab. The maximum particle displacement, s_{max}, is related to the pressure amplitude by

$$\Delta P = \rho c_\ell \omega s_{max} \,. \tag{6}$$

The maximum strain, $\Delta L/L$, caused by the wave is approximately the maximum particle displacement divided by the wavelength, λ. This is only valid for wavelengths smaller than the body of the crab. For longer wavelengths the strain will be much less. This gives an approximate expression for the strain

$$\frac{\Delta L}{L} \approx \frac{\Delta P}{\rho c_\ell \omega \lambda} = \frac{\Delta P}{\rho c_\ell^2} \,, \tag{7}$$

from which we see that the maximum particle displacement does not depend on the frequency of the sound. For 255 dB sound the above expression gives us a maximum strain of 2.2×10^{-3}. This is only about 2% of the elastic limit estimated above. So, unless the full calculation shows significant focusing of the sound we should not expect to see damage to crab tissues via this mechanism. If significant focusing is seen then the points in the crab where the waves are focused will experience much higher intensity and this may put them at risk of damage. If the amplitude of sound at any point inside the crab is more than about 50 times the amplitude of sound outside the crab then there is reason for concern that the tissues may be near or beyond their elastic limits.

While, according to the simple analysis above, the maximum particle displacements are too small to cause physical damage to tissues, they are significant. In absolute terms a piece of tissue within the crab might experience oscillations with an amplitude up to 0.2 mm. This is certainly large enough that the crab ought to be able to feel it. Hence, a behavioural response is to be expected even if crabs cannot hear. Additionally, while no individual tissues should be damaged by the pulse, it is plausible that displacements of this size might cause the separation of the outer membrane of the ovary that is reported in [1, Chadwick, 2004]. Much more study would be required to establish whether this is possible since the strains necessary to separate this membrane from the organ is not known.

Sound Intensity Within the Crab

To estimate the sound intensities within the crab we will use methods from fundamental theory of acoustics. The calculation essentially follows the procedure used in [16, Machlup, 1952] and in [7, Hasegawa, 1978]. The calculation is highly technical so only a brief sketch of it will be given here. The seismic pulse is separated into its individual frequency components and each component is treated as a plane wave traveling downward. The crab will be treated as a thin spherical shell of elastic material (the carapace) filled with a viscous liquid (the tissues). The sound waves are local displacements $\mathbf{s}$ of elements of the material that they are traveling through. In the fluids (water outside the shell, tissue inside the shell) the displacements can be described as the gradient of a scalar displacement potential, ψ,

$$\mathbf{s} = -\nabla\psi \,. \tag{8}$$

In the solid shell transverse waves are allowed so the displacements can be expressed as

$$\mathbf{s} = -\nabla\psi + \nabla \times \mathbf{A} \,. \tag{9}$$

where $\mathbf{A}$ is a vector displacement potential. According to linear theory of acoustics the displacements obey the homogeneous Helmholtz equation so that

$$\nabla^2\psi + k_\ell^2\psi = 0 \tag{10}$$

and

$$\nabla^2\mathbf{A} + k_t^2\mathbf{A} = 0 \tag{11}$$

where $k_\ell = \omega^2\rho/(K+4\mu/3)$ where K is the bulk modulus of the material and μ is the shear modulus of the material (zero for liquids) and where $k_t = \omega^2\rho/\mu$. The solutions of the homogeneous Helmholtz equation are waves which are described, in spherical components, as linear combinations of spherical Bessel functions. We must apply boundary conditions at the inner and outer surfaces of the shell. The boundary conditions are that the displacements perpendicular to the surface

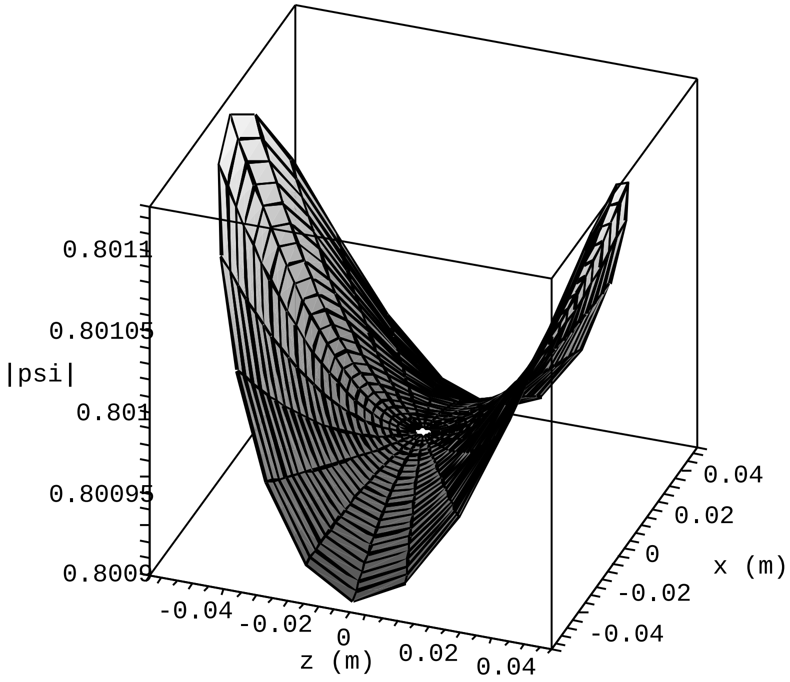

Figure 2: Magnitude, $|\psi|$, of the displacement potential inside a 10 cm radius crab for sound with a frequency of 100 Hz. The view shows a vertical cross section through middle of the crab with up (the direction that the sound is coming from) roughly to the right in the figure. The vertical scale is set so that $|\psi| = 1.0$ indicates sound of the same amplitude as the incident wave.

must be the same on both sides of the surface (the surface of the fluid does not leave contact with the surface of the shell), the force exerted by one material on the surface is the same as the force exerted by the other material (this is just Newton's third law), and the tangential stress in the shell vanishes at the boundary (because there can be no tangential stress in the fluid). This gives rise to a series of equations which can be solved for the undetermined coefficients in the sums of spherical Bessel functions that describe ψ and $\mathbf{A}$. The best presentation of the calculation just described is in [16, Machlup, 1952]. However, that paper predates the sorts of computer applications that can be used to obtain full solutions of the resulting equations so it presents only approximate solutions that are valid in various limits. In the present study the software package, Maple, was used to find full solutions to the equations so that the solutions can be plotted and examined.

Once these solutions are obtained the amplitude of the waves can be found at all points in the crab. Solutions for various frequencies of incident sound are shown in Figure 2, Figure 1 and Figure 3. The figures show the magnitude, $|\psi|$, of the displacement potential inside the crab. They show a vertical cross section through the center of the crab with up (the direction that the wave is coming from) roughly to the right in each graph. The magnitude of the displacement potential at any location is proportional to the amplitude of sound at that point. In the figures the vertical scale is set so that 1.0 indicates the amplitude of sound outside the crab.

As can be seen in Figure 2, for 100 Hz and 10000 Hz sound the sound amplitude at all points inside the crab is smaller than the amplitude outside the crab. However, it is not smaller by a large factor. For 100 Hz sound the amplitude is no less than about 80% of the outside amplitude while of 10000 Hz sound the amplitude is no less than about 40% of the outside amplitude. For 30000 Hz we see that at some points inside the crab the sound amplitude is higher than the amplitude outside the crab. The wavelength of the sound at this frequency is about the same as the size of the crab and so we see standing wave effects as well as more significant "focusing" of the sound. Nevertheless, the largest amplitudes inside the crab are only about 40% higher than the amplitude outside the crab. We do not see an increase in amplitude of anything like the factor of 50 that would be required for the crab's tissues to be near their elastic limits. There might be more focusing and more pronounced standing wave effects at frequencies above 30000 Hz, but very little of the sound in a seismic pulse is at frequencies higher than 30000 Hz so this should not be of any concern. For sound in the 100-300 Hz range the sound intensity is somewhat less than that outside the crab. This is the dominant frequency range for a seismic pulse.

Hence, at all frequencies, the sound amplitude inside the crab is approximately the same (within a factor of 2 or so) as the amplitude outside the crab. Therefore, the analysis of the preceding sections is valid. We conclude that the tissues in the crab do not reach their elastic limits as a result of even a 255 dB seismic pulse.

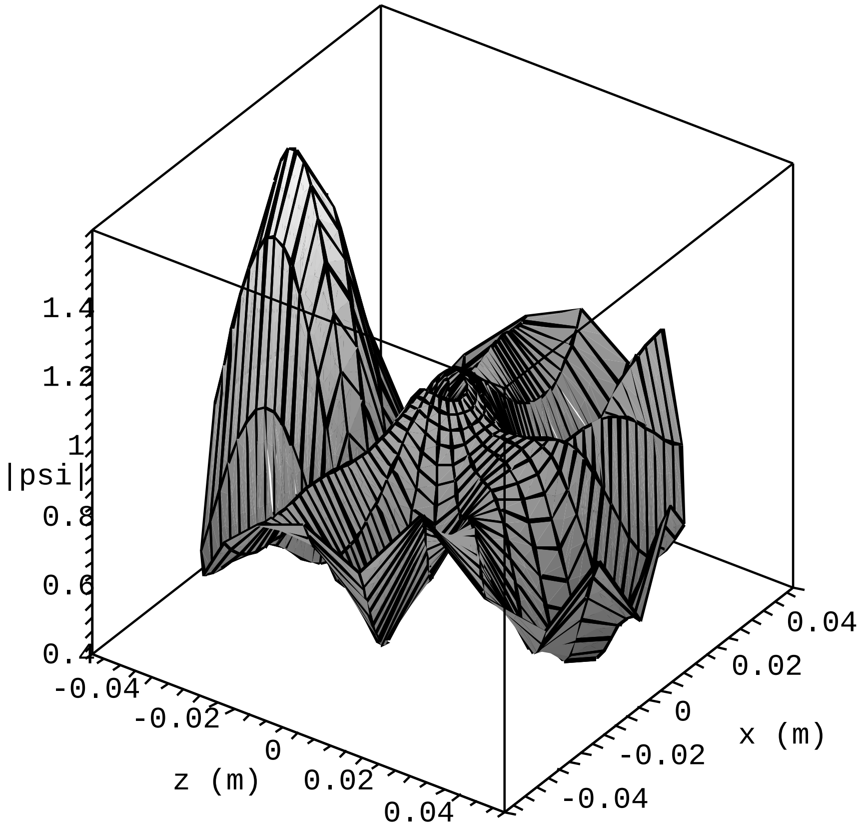

Figure 3: Magnitude, $|\psi|$, of the displacement potential inside a 10 cm radius crab for sound with a frequency of 30000 Hz. The view shows a vertical cross section through middle of the crab with up (the direction that the sound is coming from) roughly to the right in the figure. Note the location near the bottom of the crab (at a negative value of z) where the sound amplitude is larger than the amplitude outside the crab.