Of seas and surgeries: acoustics of the future

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What links tumour therapy, ocean waves and opera halls? The answer is acoustics, as demonstrated by a recent meeting with the theme "The sound of the future: a global view of acoustics in the 21st Century"*. With over 2000 delegates from 49 countries, the meeting presented a truly international perspective on the latest acoustics research. Topics ranged from architectural and structural acoustics, through the use of ultrasound in medicine and oceanography, to the perception of sound by people and animals.

Most of us are familiar with biomedical applications of acoustics. In the UK alone over 250 000 foetal scans are produced using ultrasound every year, together with over one million physiotherapeutic treatments. But we could be equally familiar with a whole range of new applications by the next century. Ultrasound at megahertz frequencies has a wavelength of a millimetre or less in human tissue, which allows it to be focused into small regions of the body several centimetres below the skin. The focusing heats the target region to core temperatures of over 80 °C in a few seconds. Cells in the target region are destroyed while leaving the skin and overlying tissues unharmed.

This technique, known as focused ultrasound surgery (FUS), was proposed over 40 years ago, but trials of the technique have only become possible since advances in medical imaging (including ultrasonic imaging) have allowed tissues to be targeted with sufficient accuracy (see "Sound therapy" by Lawrence Crum and Kullervo Hynenen *Physics World* August 1996). Gail ter Haar described a joint project between the UK Institute of Cancer Research and the Royal Marsden Hospital to explore how FUS could be viable for treating cancer. In the first phase of the trial patients were treated on an outpatient basis, without anaesthetic or sedation. Although no attempt was made to provide a complete treatment, the focused ultrasound did destroy the targeted parts of kidney, prostrate and liver tumours. The second phase, which will attempt to cure cancers of the liver and prostate, is due to start in the autumn.

Wave power – the bubbles that are underneath breaking waves can provide important information about ocean processes

Other biomedical applications addressed at the conference included advances in the current clinical practice of using ultrasound to destroy kidney stones, and the use of echo-contrast agents to improve the information available from ultrasound scans. Possibilities for future clinical applications were also discussed, including acoustic microscopy, and the use of ultrasound to enhance the delivery of drugs and to prevent bleeding – nearly 40% of battlefield deaths arise through loss of blood.

Acoustic propagation at longer wavelengths and through much larger bodies of liquid – the oceans – was another theme. As Robert Urick wrote in 1983: "Of all the forms of radiation known, sound travels through the sea the best." Sonar applications are now well known, but researchers revealed many fascinating examples of exploiting acoustics in the ocean.

For example, the ambient noise of the ocean was once studied as a source of noise in passive sonar applications, such as the detection of submarines from the sounds they can generate. But this ambient noise could also be used to monitor environmental processes such as rainfall over the oceans.

Similarly, in active sonar applications acoustic signals are projected into the ocean. Such techniques have previously been used, for example, to detect submarines but the same technique is now being used to make environmental measurements. Acoustic signals detected at ranges of over 1000 km from the source might be analysed to determine the thermal characteristics of the ocean, which could lead to measures of global warming. Indeed, it is interesting to note that the top 2.5 m of the ocean has the same heat capacity as the whole of the atmosphere.

David Farmer of the Institute of Ocean Sciences in Sidney, British Colombia, Canada described acoustic investigations of the top 10 m or so of the ocean. This layer is responsible for the transfer of momentum, energy and mass between the atmosphere and the ocean. Some 2–4 gigatonnes of atmospheric carbon, for example, is believed to dissolve into the ocean each year, and a significant amount is also released from the ocean to the air.

The upper ocean presents a challenging environment for scientific study, both in terms of the ruggedness required of the measuring equipment and the interpretation of the scientific data. Sonar images and acoustic Doppler information are used to measure the structure and motion of waves and bubbles. Bubbles generated by breaking waves can not only be used as tracers for subsurface currents and circulations, but also are directly relevant to the transfer of gases between the ocean and atmosphere.

Farmer described how the number of bubbles in the uppermost layer can be measured by placing acoustic resonators just below the sea surface to measure the change in the speed of sound and the damping caused by bubbles in the seawater. This and other emerging techniques detect the size distribution of bubbles. Since the radius of a bubble is influenced by the amount of dissolved gas and its buoyancy – among other things – measurements of bubble sizes provide insights into the small-scale processes beneath breaking waves.

Another notable example of the role that sound can play in liquids was provided by Tim Mason of Coventry University in the UK, who gave a live demonstration of the chemical effects that ultrasound can generate. An impressive sequence of chemical reactions assisted by ultrasound included ultrasonic degassing, luminescent reactions and the erosion of metal foil to produce small holes or "pits". Mason also used sound to produce emulsions and to cause particle agglomeration in an aqueous suspension of copper bronze.

Presentations on sound in liquids accounted for only about one quarter of the technical presentations. Some of the other topics discussed included the acoustics of opera houses, speech and hearing, noise pollution, musical instruments, and the use of sound by insects and birds.

The results reported at the conference are recorded in four volumes of proceedings edited by Patricia Kuhl and Lawrence Crum of the University of Washington in Seattle. Together with the various organizing committees, they can take credit for an impressive meeting. With memorial sessions for Manfred Heckl, Isadore Rudnick and Hugh Flynn – three people who have contributed enormously to the development of acoustics in this century – the conference certainly showed that acoustics has a distinguished past and an exciting future.

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Microscopes get to the point

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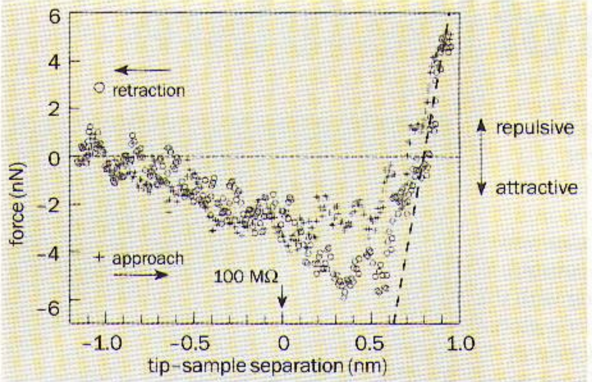
The forces between atoms determine the basic physical properties of materials. They also play a central role in physical phenomena such as adhesion, friction and lubrication, as well as the interactions between biological entities such as proteins, DNA and cells. In the same way, interactions between a sample and a sharp tip play a major role in understanding the imaging mechanisms in a scanning tunnelling or atomic force microscope. These microscopes use tunnel currents or forces between the tip and sample to image and characterize surfaces on an atomic scale.

Researchers at McGill University in Montreal, Canada, and IBM's Zurich Laboratory have now measured the adhesion interaction between a gold sample and a tip consisting of only three tungsten atoms (G Cross *et al.* 1998 *Phys. Rev. Lett.* **80** 4685). This is the first time that the interaction forces have been measured for different separations between a sample and a well defined tip. Although the shape and composition of the tip have a significant effect on the interaction, previous investigations have not been able to determine its exact geometry. The new results have important implications for a variety of fields, ranging from tribology to the study of chemical bonds.

The team used a combined atomic force/scanning tunnelling microscope operating under ultrahigh vacuum. The experimental set-up also included a field-ion microscope (FIM) to fabricate the tungsten tip and examine its shape before and after the measurement.

To measure the adhesion force, a clean gold sample was mounted on a stiff glass cantilever. The interaction between the tip and sample was measured by using a differential interferometer to detect deflections induced in the cantilever. This arrangement means that the force can be measured with a resolution of less than a nanonewton as the tip is brought towards the sample. Conventional atomic force microscopes (AFMs) measure very small forces by using soft cantilevers, but these "jump" into contact with the sample when the force between the tip and sample becomes comparable with the stiffness of the cantilever. This means that stiff cantilevers are needed to measure force–distance curves.

The researchers measured the interaction force as the separation between the tip and an atomically flat surface was varied. The tunnel current was measured at the same time, and the results show that the operation of a scanning tunnelling microscope (STM) creates a substantial force interaction between the tip and sample. As the tip is brought towards the sample, it first experiences an attractive force. But at closer distances the interaction force quickly becomes repulsive.



The interaction between the tip and sample was measured as the tip was brought towards the sample (+) and then gradually taken away (o). The tip–sample separation is defined as the relative motion of the tip with respect to the substrate, using a tunnel resistance of 100 MΩ as a reference point. Forces greater than zero are repulsive, and forces less than zero are attractive.

Once the repulsive force reached about 5 nN, the team pulled the tip back until the force dropped to zero. When the tip was retracted further, the researchers found that the force remained attractive over a distance of about 1 nm. This contradicts the universal theory for adhesion, which estimates that the attractive force should decay over a distance of about 0.1 nm. Moreover, no sudden jump in adhesion was observed, as was expected from simulations and previous observations of metallic contacts between samples and a gold tip.

The force–distance curve shows some hysteresis between the approach and the retraction of the tip, suggesting that a small amount of energy, about 7 eV, is lost during the experiment. This dissipative process is most probably caused by the displacement of gold atoms close to the contact region. The oscillations in the force–distance curve are perhaps another indication of the gold atoms becoming rearranged under the pressure of the tungsten tip.

The repulsive part of the curve suggests that the contact pressure between the tip and sample is around 25 GPa, about 100 times larger than the yield strength of bulk gold. The structure of the tip shows virtually no change after the measurement process, even though two atoms had become adsorbed onto the sidewalls (see figure). Indeed, it is astonishing that a tip consisting of just three atoms can sustain such high pressures, about 2 nN per atom, without any irreversible effects.

In 1990 Don Eigler of IBM showed that STMs could be used to manipulate individual atoms to create artificial structures and molecules on surfaces. An understanding of the basic mechanisms that lie behind this type of manipulation, together with the forces associated with the process, will help us to understand wear, friction and tribology at the atomic scale.

Recently, AFMs with stiff cantilevers have been able to image a sample without touching the surface. These "non-contact" AFMs work by detecting the change in the resonance frequency of the cantilever due to the force between the tip and the sample. Such instruments have achieved true atomic resolution when used to image the surfaces of various semiconductors and a few insulators such as sodium chloride. However, they have not been able to image the surfaces of classical insulator surfaces such as alumina and magnesium oxide, which cannot be characterized by other means.

Despite the success of non-contact AFMs, the imaging mechanisms are still not well understood. And although they can image surfaces at the atomic scale, they are not yet sensitive enough to resolve force–distance curves. The results from the McGill–IBM collaboration have not solved these problems, but provide a big step forward in the right direction. The experiments have shown that it is possible to define the tip geometry independently and to measure the force–distance curves between a sharp tip and sample to high resolution, given the proper instruments.

However, it is an arduous task to check the tip geometry by using a field-ion microscope with an AFM/STM. A good indication of tip sharpness, used by most researchers, is whether or not the microscope provides atomic-scale resolution. But force–distance curves are useful in their own right, since they should make it possible to determine the bond strength of atoms under the tip, and perhaps even to identify them.

The natural development would be to combine force–distance spectroscopy with surface imaging using non-contact AFMs. Such a combination of measurements will undoubtedly answer many questions, but may also generate many more.