Ultrasound – hear no ultrasound, see no ultrasound ... forget ultrasound? Part 1

Author David R Andrews or Cambridge Ultrasonics Ltd

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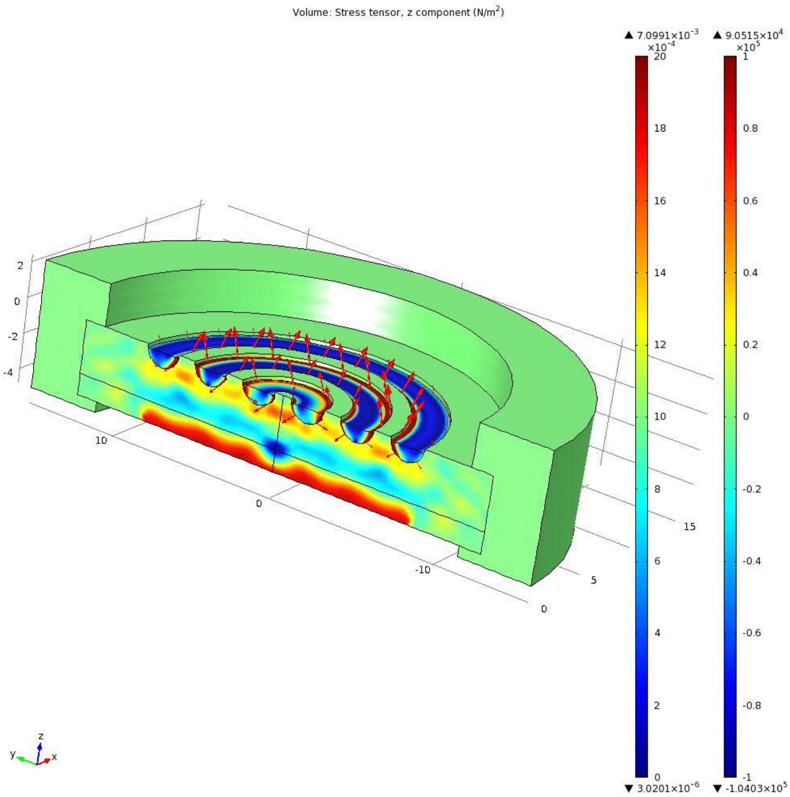

Finite element model of a liquid lying in grooves in a metal plate. Colours show the z-component of the stress tensor in the metal. Arrows show the displacement of the liquid and the direction of motion.

The physics and applications of ultrasound are nothing short of … eminently forgettable! Can you think of a significant invention by man that uses ultrasound? Bats don't count because they were not invented by humans; whales and dolphins don't count for the same reason.

Perhaps it's because we can't see ultrasound and we can't hear it that we forget about it but ultrasound has more science in it than you might at first think and probably many more applications than you ever imagined. As examples of the advanced science in ultrasonic devices consider, firstly, that nearly all transducers delivering power ultrasound are more akin to mode-locked lasers than cheap loudspeakers and, secondly, researchers have also been devising invisibility cloaks for ultrasound.

Thinking about examples of common applications: there are probably close to a billion vehicle parking sensors that use ultrasound around the world; ultrasound is also used to shoo-away unwanted visitors such as rats, mice and adolescents near shop windows. Rodent scarers work at frequencies above 20 kHz, making them truly ultrasonic according to the definition but adolescent scarers are pitched at more like 17 kHz, which is not strictly ultrasonic but the majority of the adult population cannot hear at that frequency, whereas adolescents can. 17 kHz sounds horrible and makes adolescents move away from shop fronts fitted with these near-ultrasonic devices; apparently, the incidence of vandalism and theft goes down where these scarers are in action. It's a sad observation that modern society treats its unruly adolescents literally like rats and so it is poetic justice that adolescents have ring-tones working at 17 kHz on their mobile phones and they can sneakily use them at school without teachers knowing.

Audio is defined, somewhat arbitrarily, as the frequency range from 20 Hz to 20 kHz and frequencies above 20 kHz are considered to be ultrasonic and below 20 Hz are infra-sonic. I can't hear sounds above 10 kHz these days but it doesn't stop me from enjoying music and talking because those two activities generate sounds at much lower frequencies: from about 150 Hz to about 3 kHz. So slightly impaired high-frequency hearing is no real disadvantage for human beings – not so for bats.

Another unexpected application of ultrasound is high fidelity loudspeakers. Bowers & Wilkins loudspeakers include high frequency units that work up to 40 kHz. Why 40 kHz when most of B&W's customers don't hear much above 10 kHz? The answer is that ultrasonic response from loudspeakers gives better dynamic response to sharp sounds like percussion, for whichFourier transformation of recorded sounds shows that harmonics extend well into the ultrasonic frequency range. The latest digital sound cards for PC gaming, such EVGA's Nu Audio, sample audio digitally at 384 kSamples per second, which is almost 20 times higher than the upper limit of human hearing, and they replay sounds at analogue frequencies up to 60 kHz, presumably, to give good quality transient sounds for high action gaming.

On a good day a soprano singer can reach an F6 note (about 2 kHz – not ultrasonic) and generate ultrasound indirectly thanks to the non-linearity of the air. High pressure sounds travel through the air non-linearly: the high pressure half-cycles of sound waves travel faster than the low-pressure half cycles, which turns a sine-wave into a triangular-wave and Fourier transformation shows that triangular waveforms must contain odd-order harmonics: 3rd, 5th, 7th, 9th, 11th …. of the frequency of the original sine-wave. Some of the harmonics from a soprano can extend into the ultrasonic region when she reaches her high notes at high volume.

Non-linear propagation of ultrasound in air is harnessed to make audio in another unusual application of ultrasound, in which a transducer generates ultrasound at two different frequencies, say, 60 kHz and 61 kHz. Provided the ultrasound is sufficiently powerful then non-linear effects occur in the air through which the ultrasound is travelling. As well as generating harmonics of the two ultrasonic frequencies, non-linearity of the air also mixes them, generating the sum (121 kHz) and difference (1 kHz) of the two frequencies. The difference frequency of 1 kHz is audible, the sum frequency is not. An electronic unit electronically shifts-up in frequency any audio signal such as speech or music so that 1 kHz is shifted up to 61 kHz and 2 kHz is shifted up to 62 kHz and so on. The transducer converts the two electrical frequencies: of fixed 60 kHz and shifted audio+60 KHz, into waves in air with the same two frequencies. The air itself creates the difference frequency = 61 – 60 KHz = 1 kHz which a listener can hear. Because it is ultrasound that is transmitted (not audio directly) and because the wavelength is short, about 5 mm at 60 kHz, and because the diameter of the transmitter is much larger, typically 500 mm, then the ultrasonic beam is highly collimated – like a search light but a collimated beam of ultrasound instead of light – and this creates a highly localised sound source. A few years ago Tate Modern had a number of these audio search lights arranged above exhibits so that as a visitor moved close to look at an exhibit she/he would hear an audible explanation about the work of art at which they were looking but people at neighbouring exhibits would not be disturbed and could hear instead information pertinent to the exhibit they were viewing (if fitted with similar audio spotlights). More recently, when the USA resumed diplomatic relations with Cuba, it was thought that ultrasound from similar transducers was being emitted towards US diplomats while they slept in their Cuban hotel rooms, resulting in the diplomats feeling unwell – investigations proved that this diplomat scarer was not an ultrasonic device and that the diplomats were suffering from mild food poisoning.

Power ultrasound is generated almost exclusively from two very similar types of transducer called Langévin and Tonpilz (sound mushroom). Each type of transducer has a semi-solid rod of metal with one, two or four piezoelectric discs included in its length. Each assembly of metal rods and piezoelectric discs has a rich vibration spectrum, irrespective of design, with many eigenmodes of vibration. The mode of interest has longitudinal, compression waves travelling along the rod that are reflected from its ends. When a frequency of electrical excitation is applied to the piezoelectric discs at the same frequency as the longitudinal eigenmode of interest then a standing-wave pattern is established in the rod with the two ends of the rod having maximum vibration, or antinodes, and a node of almost zero vibration at approximately half way along the length of the rod. These assemblies are half-wavelength, high quality (Q) factor, mechanical resonators with the piezoelectric discs pumping the resonator at its resonating frequency. Due to the high quality or Q factor of the eigenmode, the mechanical amplitudes at the antinodes grow large, giving the high amplitude of vibration that is desired. The principle of operation is very similar to a mode-locked laser, which has a high optical-Q cavity of controlled length and mirrors at its ends, so that light can be internally reflected back and forth. It is the multiple internal reflections that increase the amplitude of light in the cavity to generate a standing wave pattern of high intensity light. There are strong similarities between the Langevin ultrasonic transducer and mode-locked lasers.

Power ultrasound is used for processing materials. Paul Langévin discovered that the sound emerging from one of the ends of his design of power transducer could be used to stun or to kill fish in water. Dolphins and some whales are believed to use their underwater sound systems in the same way. Other uses of power ultrasound include: cleaning objects, cleaning teeth, activating surgeons' scalpels to help cut bone in surgery, massage, breaking kidney and gall stones, processing sewage to homogenise it and to kill bacteria, breaking-open algae cells to release oil that can be used to replace fossil fuels, cutting cakes in bakeries, welding plastics together in shoe factories, welding metals and detecting holes in gaskets around doors. In chemistry research, power ultrasound is used to cause cavitation in liquids such as water to make new, short lived unusual chemicals. Cavitation bubbles are created during the rarefaction half-cycle of intense ultrasound, during which time gases diffuse into the bubble from the surrounding water, then, during the strong compression half-cycle of the ultrasound, the cavitation bubble collapses rapidly producing exceptionally high adiabatic pressures and temperatures. Conditions of high pressure and high temperature create the unusual chemicals of interest to chemists. If the ultrasound has a frequency of 25 kHz then the compression half-cycle lasts 20 µs and the unusual chemicals last for only some fraction of this time – but long enough for spectrometers to detect their existence.

The mathematical theory of sound and ultrasound was partly developed by Lord Rayleigh in the Victorian era: in 1877 he published a book called “The Theory of Sound”. Sound propagates in gases and liquids by scalar, longitudinal, compression waves; however, in solids, sound can propagate not only by scalar compression waves but also by vector, transverse, shear waves. At free surfaces it is possible for compression waves in solids to generate shear waves and vice versa, making for highly complex mathematical problems that can only be solved when there is simple geometry or certain approximations are imposed on the solution, such as small amplitude linear solutions. Lord Rayleigh started a field of mathematical endeavour to try to find algebraic solutions for many problems involving sound propagation. With the advent of relatively easy-to-use finite element programs, for example Comsol, it is now possible to calculate numerically how ultrasound will travel even in complex geometries and with non-linear propagation – something Lord Rayleigh could only have dreamt of doing. Numerical modelling is helping to improve our understanding of ultrasound and how to make better or novel transducers. Multi-physics finite element programs permit the modelling, for example, of laser-induced ultrasound or the effect of heat generation on power transducers or a whole range of other physics connected with ultrasound. This is an exciting field for physicists in, what I hope you now agree, is an eminently unforgettable science and technology.

Ultrasound – hear no ultrasound, see no ultrasound, forget ultrasound? Part 2

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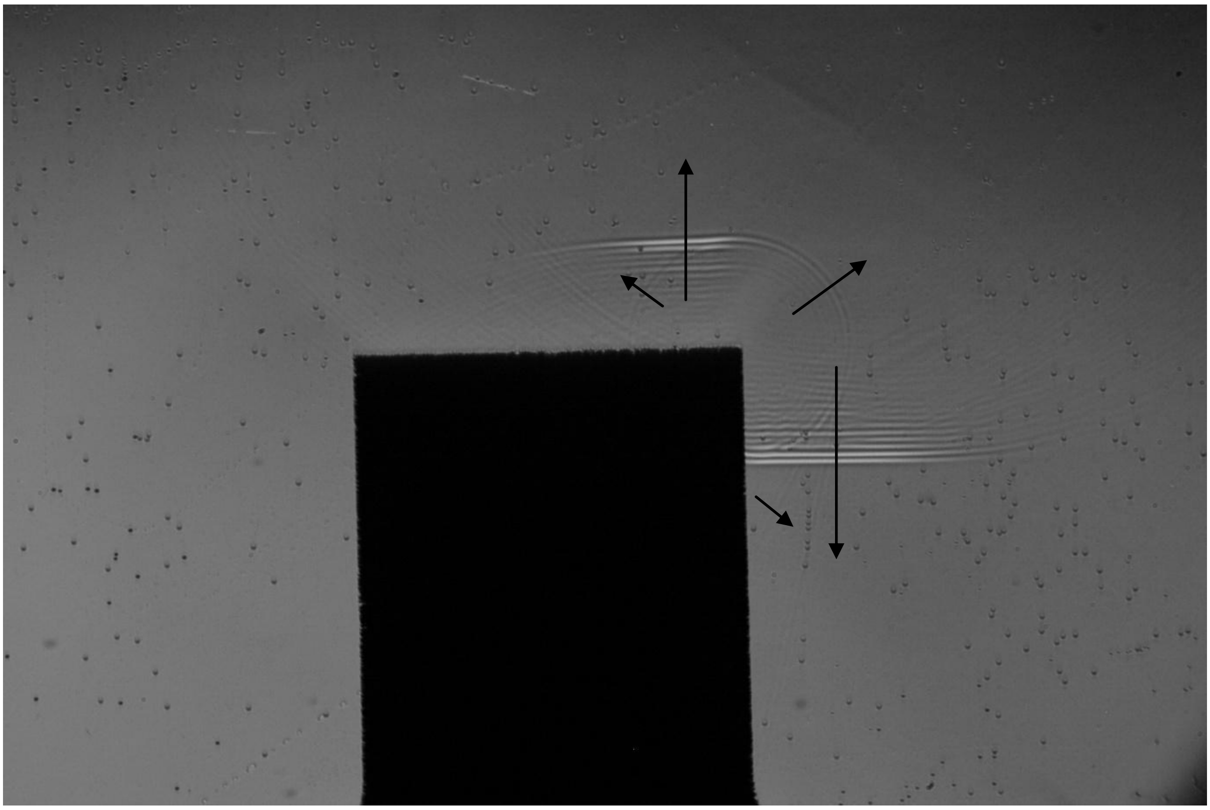

Ultrasonic plane waves at 1.5 MHz in water travel from top to bottom of the picture and are scattered by an aluminium block (black square).

The physics and applications of ultrasound are nothing short of … eminently forgettable! Can you think of a significant invention by man that uses ultrasound? This is part 2 of an article that sets out to disprove the myth that ultrasound is eminently forgettable.

When ultrasound is not being used to process materials it is frequently being used to probe into materials to learn something about them. All man-made probing using ultrasound is copying what the animal World has done for millions of years: bats are the masters of probing the air and probably dolphins and whales are masters of probing the water. We have much to learn from them.

Bats are known to navigate using short bursts of ultrasound and their skill in signal processing of ultrasonic chirps and bursts challenges man's ingenuity in related technological fields and is often a source of inspiration to designers of ultrasonic systems, such as myself. Baby bats unusually emit sounds at lower frequencies than their parents; by contrast, human babies emit sounds at higher frequencies than their parents. It all comes down to the size of the vocal chords – babies have smaller vocal chords than adults just because of their smaller body size so they make higher frequency sounds. So, why to adult bats make sounds that are higher in frequency than their babies? The answer is that baby bats have to learn to use their voices in a falsetto mode, like their parents, in order to reach the very high frequencies they need for hunting. Higher frequencies give better axial resolution, which needs to be sufficiently fine to detect and to hunt the hundreds of tiny moths and mosquitoes every bat catches every night. Bats also emit high intensity ultrasound and mechanically dampen their eardrums to prevent damaging them during transmission (a bat with tinnitus has a serious problem!).

The high intensity of ultrasound used by bats must also generate harmonics in the air by non-linearity (see Part 1 of this series of articles) and it is possible that these higher frequencies are used to advantage by bats for locating their prey – exploitation of non-linear effects in air may give bats even higher frequencies to exploit. What is so wonderful about higher frequencies? The answer is bandwidth and axial resolution; at higher frequencies it is generally possible to get a wider range of frequencies (bandwidth) and wider bandwidth results in finer axial resolution. The mathematics used to understand axial resolution and bandwidth are the same as is used to explain Heizenberg's Uncertainty Principle, one of the cornerstones of quantum physics. There are many links between ultrasonics and quantum mechanics.

Bats and human beings are both mammals, so do humans have an echo-location system as good as bats? The simple answer is no but humans do have some of the same abilities and to a remarkable degree. I have given many lectures where I ask the audience to close their eyes and hold out one straight arm with a pointed finger; the audience has to point their arms and fingers at me while I move silently about the lecture theatre making occasional noises. The results are astonishing: virtually every person in the audience points directly at me with very high lateral angular precision (I assume that no one has ever cheated and opened their eyes) – humans have learnt to develop exceptional precision for locating sound sources laterally. Bats can almost certainly do the same thing but with one important difference: it is the bats themselves that emit sounds and then listen to echoes from nearby objects.

Here's another human echo-location experiment for you to try. Next time you are near a large flat surface, like a wall or a cliff, next to a safe, flat open space (not indoors), make short shouts and listen for the echo. Try moving closer to the reflecting surface then farther away while occasionally shouting, repeating the experiment at different distances, and you should notice that the time it takes for the echo to reach you increases with your distance from the wall. With a little practice, you should be able to estimate your position relative to the surface even with your eyes closed just using sound. With a little more practice you should discover that short duration, high frequency shouts work better than low frequencies: young children should be better than old people in this experiment unless adults have good falsetto voices. If you had to hunt for your food at night, when you can't see your prey, you might try using echo-location but you would quickly discover you really must use a high-pitched falsetto voice to have much success. In addition, your prey might hear you coming with all the noise you are making and they might even try emitting confusing sounds to help them avoid you. There you are: human echo-location like bats!

Ultrasound is used for probing or inspecting many things by humans and the principle of operation is copied from bats. Objects that humans inspect include: human bodies, animal bodies, pressure vessels, pipelines, railway tracks, aircraft wings and fuselages, silicon wafers used to make integrated circuits, locating objects close to motor vehicles when parking and ultrasonic tape measures for quickly measuring the sizes of large rooms - to name but a few. I have not included sonar because it is not strictly ultrasonic but it is a dolphin-like echo-location system working in water and generally in the audio range but using identical principles to bats. Some man-made sonar systems use non-linear propagation in water (see Part 1 of this series) and synthesize a large aperture array in the water that results in a narrow search-light-like beam of low-frequency sound. At first glance it appears to be like the ultrasonic search light mentioned earlier in Part 1 of this series of articles and, while there are similarities, the sonar version has an extra level of complexity that I won't go into here.

Inspection of human bodies is probably the most technologically advanced of all man-made ultrasonic applications and makes use of arrays of many small piezoelectric transducer elements working at between 1 MHz and 5 MHz. The speed of sound in water is 1500 ms-1 so the wavelength at 1 MHz is 1.5 mm and this gives an indication of the axial resolution of these systems - human soft tissue is very much like water (as far as the propagation of ultrasound is concerned). Arrays provide many advantages. With an array you can electronically create a wide range of transmitted waveforms using constructive and destructive interference of the waves that each element generates. Examples of wave-beams that can be created by arrays are: diverging, colimated and focused beams. The latter are mainly used in medical scanners and industrial scanners for non-destructive testing. A computer controls when each piezoelectric element in the array is excited by an electrical pulse, thereby launching its own ultrasonic pulse. By controlling the time delays between driving all the elements, it is possible to make the pulses interfere constructively to form a focused point. Any focal point of the pulses can be moved around inside the test sample, or human body, under software control. Where the ultrasound is most intense, at the focus, the sample there nearly always generates the strongest echo. A picture of the interior of the sample can be created by scanning the focal point through the sample under test using software control and showing the differing intensity of the echo at each focal point on a computer screen.

I like to refer to the above scanning method as transmit beam steering (TBS) but there is another method that can be used that employs received signals, it is called: synthetic aperture focusing (SAF). In this latter method, any kind of transmitted beam can be used including a diverging beam of ultrasound. The beam of choice is emitted by a transmitter into a region of the sample under test and echoes are generated from any objects found there. Some echoes return to the transmitter, which also acts as a receiver. Echoes come from objects such as: bone in the human body or cracks in metal or moths in air. Echoes are collected preferably by multiple receivers, ideally a 2-dimensional array of many receiver elements – a transmitter array can also be used as an array of receivers. It is possible for a computer program to synthesize the focusing of the echoes to create an image of the test sample at any distance and in any plane simply by adjusting time-shifts between the various received signals and adding all the signals together. SAF has been used to generate images in concrete and SAF is also used more commonly in radar, for which it was first developed. Medical ultrasound scanners all use TBS because images are generated quickly and in real-time. SAF is slower to generate an image because an algorithm has to process large quantities of data for each image.

In human bodies, various organs can be scanned to look for defects or damage and unborn babies can be examined to check for abnormalities or problems affecting the baby that can be treated.

Cracks in pressure vessels can be detected using ultrasound at frequencies between about 0.5 MHz and 5 MHz. The speed of sound in many metals is approximately 6,000 ms-1 and the wavelength at 1 MHz is 6 mm, which gives in indication of the axial resolution of the method. The aim of inspection is to detect a crack before it grows to reach a critical size at which it can cause the pressure vessel to fail catastrophically and potentially explosively. If a single transmitter/receiver is used and not an array of transducers then the transmitter/receiver must be moved slowly over the surface of the sample to find an echo from a flaw. Lateral resolution now depends upon the width of the ultrasonic beam, which may be 10 mm or more. This is the traditional method of non-destructive testing but, here too, array technology is replacing the older manual scanning method. Differences in arrival times of compression waves and shear waves can also be used to determine the position of a flaw.

Non-linear propagation effects are stronger in liquids, like water, than in gases like air. The human body is very much like water, except for the bones. There is a problem with the non-linear propagation of ultrasonic waves in the human body: harmonic generation makes the focus very sharp and it is possible for high pressure transients to be created this way. Sharp pressure transients are absorbed rapidly by most materials including the human body, with mechanical wave energy being converted into heat – any focus is generally the hottest point. However, if the focus is inside the brain of a foetus, then the raised temperature there can cause brain damage. There have been concerns that male foetus' brains are more susceptible to heat-damage from ultrasound scanners than female foetus' brains and this might explain why boys born within the last 30 years (when ultrasound scanning of foetuses has been routine) are more likely to be mentally unstable or even violent than girls born within the last 30 years; boys born, say, 60 years ago should be unaffected because ultrasound scanners were not available then. Great care is taken by the manufacturers of medical ultrasonic scanners to check that imaging pressures are never too high.

Every cloud has a silver lining: heating caused by increased ultrasonic pressure and non-linear transient pressures can also be used to advantage. Ultrasound scanners using arrays can be used to generate heat deliberately (HIFU) in the human body, thereby killing cells such as cancer tumours. At low intensity, the ultrasound scanner is used to image the tumour and locate its position then, working at high intensity, it can be used to focus ultrasonic power on the tumour cells only and to kill only the cells in the tumour using heat. This kind of treatment is growing in popularity because it is quicker and less invasive than surgical intervention and it targets only the tumour, unlike chemotherapy which affects the entire body. This kind of medical power ultrasound transducer is one of the few exceptions where Langévin and Tonpilz transducers are not used.

At the start of this article I made a rash statement: you can't see and you can't hear ultrasound. It's not strictly true although in an everyday sense the statement is reasonably accurate. Let's think about not hearing ultrasound first. There are people who love bats and like to go searching for them at night during the summer months. Bat-lovers are frustrated because they can't see the bats (it is dark after all and lights frighten away the bats) and they can't hear their ultrasonic squawking. Some bat-lovers use electronic devices, sometimes called bat-radios, that allow the bat-lovers to listen to the bats. The devices have microphones sensitive to the frequencies of ultrasound used by bats (between about 30 kHz and 100 kHz). Electronic signals from the microphones are mixed with a fixed frequency close to the bat frequency (giving the sum and difference frequencies – just like non-linear propagation). The sum frequency is filtered-out and the difference frequency is amplified; mixing and filtering have the effect of lowering the bat frequencies into the range that humans can hear. This mixing and filtering procedure is identical to the super-heterodyne principle that is used in virtually all radio receivers. With one of these bat detectors, the bat-lover need only tune-in to her or his favourite bat-station to hear bats hunting as they fly about. Different species of bats use different frequencies and different chirps so that bat radio can be used to differentiate between different species of bats.

Bat-radios are also sometimes used by teachers at schools to detect students with high frequency ring-tones on their mobile phones – another example of poetic justice (see Part 1 of this article).

Going back to the title, "Ultrasound - … see no ultrasound…", there are a couple of optical tricks that can be used to let us see pulsed or continuous ultrasound in transparent materials. The first trick is well-known: stroboscopic illumination. Bright, short duration light pulses are used to "freeze" the motion of sound pulses (or continuous waves) provided the ultrasound and light flashes are pulsed and synchronised. Trick number two is to provide contrast enhancement using either the schlieren or shadowgraph or photo-elastic effects. Schlieren works well with ultrasonic waves in all transparent materials: gases, liquids and solids; photo-elasticity works only in solids like glass or some polymers. Shadowgraph is a close cousin of schlieren. Photo-elasticity needs crossed polarizing optical filters either side of the sample in which the ultrasound is travelling: creating either linearly or circularly polarized light. All of the optical effects require mirrors or lenses to send collimated light through the sample within which the pulsed ultrasound is travelling. Light emerging from the sample is focused to a point by one of the lenses or mirrors where, for the schlieren and shadowgraph methods, a spatial stop is placed and a camera or the human eye looks along the optical axis towards the sample with the spatial stop immediately in front of the camera or eye. The spatial stop notionally blocks the light from the sample. By adjusting the position of the (out of focus) stop until some light starts to reach the camera (or eye), the sample becomes visible and ultrasonic waves are enhanced in contrast and can be seen as apparently stationary by the stroboscopic effect. In the schlieren method, optical contrast enhancement is caused because light rays deviated from the ultrasound in the sample are in greater abundance in the light passing around the spatial stop than light that is not deviated and which is blocked by the stop. Think of schlieren as acting like the sun-visors fitted to nearly all motor vehicles, which stops the driver being blinded when the sun is shining into the driver's eyes.

By varying a time delay between when the ultrasound is launched and when the light flashes, it is possible to follow the ultrasound as it propagates out of its transducer and on into the test sample. Rendering visible of ultrasonic waves in this way is very valuable when evaluating or debugging ultrasonic transducers and it can also be used to look at scattering of ultrasound by various objects. There is considerable synergy with results from numerical finite element modelling: a new transducer is preferably first designed using finite element modelling, where it can be tested quickly and optimized in a numerical environment, but then the optimized design can be built and tested experimentally by the visualization method described above. Development times of new transducers can be reduced and the quality of resulting transducers and systems is generally superior to ad hoc designs.

The picture at the head of Part 2 of this article shows ultrasonic waves of 1.5 MHz in water (where small bubbles are visible) traveling from a transducer (out of view) in the direction, initially, of top to bottom. The wavelength is 1 mm. An aluminium block (black square) in placed to scatter partially the ultrasonic waves. Some of the waves do not hit the aluminium block and pass down its right side. Some of the waves are reflected by the block and change direction to travel upwards. Some of the waves are transmitted into the block where they cannot be seen, however, waves in the aluminium that run close to any surface in contact with the water act as sources of waves in the water - in this case supersonic sources because the speed of sound in aluminium is 6,400 m/s whereas in water it is much slower at 1,500 m/s. Look below the strong waves to the right of the block and you should see fainter, straight waves at an angle to the surface of the block of about 14 degrees - these are waves caused by waves inside the block.

Ultrasound – hear no ultrasound, see no ultrasound, forget ultrasound? Humans can't hear it, no animal can see it directly but we shouldn't forget ultrasound. We use it but we often don't know we are using it - It is used widely in very many applications.