ELSEVIER

Ultrasonics 38 (2000) 1–5

Ultrasonics

www.elsevier.nl/locate/ultras

Human uses of ultrasound: ancient and modern

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Abstract

For untold millennia certain animals have used ultrasound to probe places where light is unavailable, echo-locating bats being among the most adept. With ultrasonics, bats can quickly and safely ‘see’ at night in pursuing insects or flying in dark caves.

Unable to hear ultrasound, humans have nevertheless made use of it. They did this anciently by taming wolves, with their keen ultrasonic hearing, for aiding in the hunt. Currently, they are doing this by developing technology to detect, generate and process ultrasound for searching in air or other gases, in water or other liquids, and in solids.

The story of these technological developments is a large and fascinating mirror of human history involving the advent of such discoveries and inventions as magnetostriction, piezoelectricity, sonar, ultrasonic microscopy, etc. – the list is long. By now we are skilled in probing for underwater objects, the internal structure in materials, organs inside the human body, etc. – again the list is long.

A number of different ultrasonic systems can be categorized into one of three key generic approaches: pulse–echo exploration, intensity mapping, and phase–amplitude measurement. In addition, each of these categories can be combined with the others to produce hybrid systems for which an unambiguous categorization is difficult or impossible.

Challenging problems remain but solutions are being found. New principles and techniques are being discovered that will improve the use of ultrasound. Employing tomo-holographic techniques to reduce ambiguity in probing three-dimensional objects, near-field techniques to boost resolution and using limited-diffraction beams to provide image construction with ultra high frame rates are cases in point.

Keywords: Holography; Limited-diffraction beams; Near-field techniques; Piezoelectricity; Pulse–echo; Sonar; Tomography; Ultrasonics; Ultrasound

1. Why this talk?

Wolfgang Sachse explained it this way: “Since this will be the last UI in this century, we would very much appreciate (you to give) an overview of ultrasonics in general (but leaving out medical/biological and high-power applications since Jim Greenleaf and Teru Hayashi will treat those subjects). …Survey what in your opinion have been the most significant developments … in this century and what we might anticipate in the next.” Leif Bjørnø emphasized this latter point by saying, “In particular we are looking forward to your predictions.” As Wolfgang wrote, “We recognize that this is a tall order … We hope … you will find it a worthy challenge.”

It’s more than a “tall order.” It’s more than a “worthy challenge.” But I have done what I can and have enjoyed the effort.

2. Background

Humans cannot hear ultrasound, but other members of the animal kingdom have long found ultrasound handy for probing places where light is unavailable. Certain animals have employed it routinely to look for otherwise unobservable objects and inhomogeneities. Echo-locating bats are among the most adept. Using ultrasound, a bat can quickly and safely ‘see’ at night or in a dark cave. The same is true of porpoises, dolphins and whales in murky ocean waters.

The sinking of the Titanic on April 15, 1912 became a big motivator for human interest in ultrasonics. Sailing at high speed about 1600 miles northeast of New York City, the Titanic, the world’s largest ship, on its maiden voyage struck an unseen iceberg and sank with 1517

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0041-624X/00/$ - see front matter
PII: S0041-624X(99)00063-3

passengers and crew losing their lives. This tragic shipwreck sparked a great deal of thought on how to prevent future occurrences of this kind.

From the beginning, of course, it was obvious that, for ultrasound to be important, the technology was needed to generate and detect ultrasonic vibrations. Soon experimenters were blowing jets of high-pressure air from narrow slits against sharp metal edges and doing similar mechanical things in order to produce the first generators of ultrasound. Later they became more sophisticated and began to employ electro-mechanical transducers based on piezoelectricity or magnetostriction to do the job.

This paper discusses the human experience with ultrasound, both ancient and modern. It focuses on the almost incredible technological developments in this area during the 20th century and attempts to suggest how new and future developments in ultrasonics may bear fruit in the 21st. In the interests of conserving space I cite only one reference which contains two pages of references dealing with much of what follows [1].

3. How ancients and moderns have used ultrasound

Anthropologists many years ago told us that primitive humans, struggling to stay alive during ice-age times, could not hear the ultrasound that would have helped them in the pursuit of game. But they could and did domesticate wolves and thus produced the world's first ultrasonic instrument, the hunting dog. To this day, this instrument is a favorite among human hunters and herders of the world.

Like our ancestors, we moderns are also interested in ultrasonic instruments. We have a great variety of problems to face in today's world. We have needed ultrasound to solve problems in such diverse areas as engineering, physics, chemistry, medicine, microscopy, underwater detection, ranging, navigation, etc. – the list is long. To a great extent our efforts have been successful.

With the ultrasonic devices now in existence we can measure the flow rate of a liquid or the speed of a moving submarine. We can put ultrasound to use in motion detectors for burglar alarms and as catalysts in chemical reactions. We can employ it for investigating the viscosity of materials, for 'seeing' into living cells, for locating schools of fish and for counting and sorting items in an assembly line.

We do all of this and much more. A comprehensive view of the huge number of applications under current research can be obtained by perusing the program for this conference. A rough count indicates more than 300 papers in over 30 different fields. For each paper, one or more applications exist.

4. Early pioneers of the 20th-century quest in ultrasonics

The real work of the world – the way we live our daily lives – has been advanced more by the products and tools produced by the technologists than by the policies and laws generated by the politicians. My heroes are the innovative engineers and scientists – the technological pioneers – who are responsible for this. The story of the 20th-century quest in ultrasonics can be told by citing their 'heroic' accomplishments. Because of space limitations I am restricted to focusing on only a very few of the early innovations. However, their accomplishments sparked the outpouring of achievement that was to continue throughout the remainder of the century.

I pick Lord Rayleigh, born John William Strutt, as my ultrasonics hero No. 1 (see Fig. 1). In 1904 Rayleigh was awarded the Nobel Prize for Physics and the next year he was elected president of England's Royal Society. Three years later he accepted the post of chancellor of the University of Cambridge, retaining this position

Fig. 1. John William Strutt, born in 1842 and succeeded to the title of Baron Rayleigh in 1873. Early in his career, he developed an absorbing interest in both the experimental and mathematical sides of physical science and in his later years was regarded as the preeminent leader in British physics.

until his death in 1919. A dedicated science writer, he worked on papers until 5 days before he died and published about 450 articles. Much of what he wrote describes his fundamental discoveries in acoustics and optics that are basic to wave propagation. His greatest book was entitled *The Theory of Sound* which to this day remains as a foremost monument of acoustical literature.

One of the first things the technologists had to learn was how to generate and detect ultrasound. The usual types of generators for air, liquids, and solids are piezoelectric and magnetostrictive. Piezoelectricity came first and was actually discovered 20 years before the start of the 20th century. It remained a laboratory curiosity for several decades afterwards.

The discoverers were two of my pioneer heroes: French physicists Pierre Curie and his older brother Paul-Jacques. Incidentally, Pierre and his wife Marie later shared the 1903 Nobel Prize in physics with Antoine Henri Becquerel for the discovery of radioactive elements.

One of the first major applications for piezoelectricity came along in World War I to produce underwater acoustic waves in an early form of submarine-detecting sonar. The pioneer hero in the latter work was Paul Langevin, another French physicist and, of course, another of my heroes.

Langevin did not have to start from scratch. He could draw on previous studies by a number of workers who had already thought of using ultrasonic waves for oceanic search. As mentioned before, much of their concern stemmed from the sinking of the Titanic. Both Lord Rayleigh and O.P. Richardson were among this group. In a 1912 interview in *Scientific American,* Sir Hiram S. Maxim, an American-born engineer and inventor, again proposed sound as a way of preventing this type of catastrophe. Inspired by what he supposed to be techniques employed by bats, Sir Hiram stated that ships could be protected from collisions with icebergs and other ships by generating sound pulses under water and detecting their echoes.

All of this, plus the awesome destructive power of German submarines served as a background for Langevin's work. An engineer, M.C. Chilowski, had by that time developed an ultrasonic device for the French Navy, but its acoustic intensity was too weak to be practical. Heading a joint U.S., British and French venture, Langevin looked into the question of how to increase the acoustic power in the water. In less than 3 years, he succeeded in obtaining high ultrasonic intensity by means of piezoelectric transducers operating at resonance. By 1918, active systems for producing and analyzing returned acoustic echoes were functioning and proving to be useful in neutralizing the U-boat threat.

The war ended a short time later, sonar having made an important contribution. The innovative work involving ultrasound continued unabated. Attention was turned from large-scale probing within the vast regions of the ocean to small-scale probing of tiny structures within the more limited region of objects of interest in factories, hospitals and laboratories. One of the most gifted of the pioneers starting in the 1920s was the Russian scientist S.J. Sokolov, whose productive work extended over the next three decades. He was one of the first to explore systematically the usefulness of ultrasound in detecting inhomogeneities such as flaws and voids within manufactured parts.

In one of his systems, the inhomogeneities were made 'visible' by reflecting collimated light from a liquid surface in a fashion similar to that of liquid-surface holography. The method was an authentic precursor of acoustic holography and predated Dennis Gabor's invention of holography by more than 10 years!

In another of his systems, Sokolov used an approach strikingly similar to that for the Bragg diffraction imagers produced in laboratories some 30 years later. In this system as well as in the holographic one, collimated light was used to read out the information developed by the ultrasound passing through the specimen being probed. Both the phase and the intensity of the sound played a part in developing the pattern of light seen on an observation screen.

In the sonar systems of Langevin, only the intensity was involved; the transmitter emitted a pulse and the intensity of the reflected pulse was used in producing the output pattern. In the above two Sokolov systems, both the phase and the amplitude played a part. With other systems to be mentioned later, the ultrasound, continuous or pulsed, is transmitted through the object or reflected from it. The sonic amplitude transmitted or reflected is then measured as a function of lateral position. The resulting amplitude map produces a meaningful pattern.

The pulse–echo, phase–amplitude, and amplitude-mapping approaches constitute conceptual bases for three fundamental types of ultrasonic probing systems. These approaches can be used as a method for categorizing systems. By now, however, systems exist that combine these approaches in such ways as to make an unambiguous categorization sometimes difficult.

The pulse–echo systems include not only sonar for oceanic search, but also linear arrays of dynamite and geophones for reflection seismology and B-scan equipment for clinical diagnosis. The phase–amplitude systems include holographic instruments for flaw detection and weld inspection. The amplitude-mapping systems include acoustic microscopes for materials inspection and biomedical analysis.

Not only did Sokolov's research involve the phase–amplitude category, but he also contributed to that of amplitude mapping. He proposed using ultrasound at 3 GHz where the wavelength of sound in water is very short (half a micrometer) and capable of resolving truly minute objects. The name he gave to the resulting device was the 'ultrasonic microscope'. Technological impracticalities prevented Sokolov from operating at sufficiently high frequencies (such as 3 GHz) for the purposes of microscopy. However, the principle he put forth (that of reading out localized electronic charge developed on a piezoelectric crystal in response to an acoustic input) has since become embodied in a well-known device called the Sokolov tube, which for a while had substantial use in low-frequency acoustic imaging. Although Sokolov was not able to produce ultrasonic microscopes, others impressed by his ideas and working more than two decades later were indeed successful.

5. Ultrasonics in the 21st century: the shape of things to come

Now comes the hard part. What will the future bring? The one thing I know for sure is that there will be surprises. But Leif Bjørnø wants more than that. He is "looking forward to (my) predictions." I know I can't predict, but I can extrapolate. Like H.G. Wells, I'll take a look at exciting present research and guess at things to come.

For example, researchers in Mexico, interested in acoustic microscopy, have recently published several papers. They work in the University of Guanajuato's Centro de Investigaciones en Optica and are knowledgeable in holography, tomography, laser-beam scanning and optical readout of acoustic information. They specialize in projects involving these and other photonics. After recently meeting with L.W. Kessler, a foremost pioneer in the initial work on scanning laser acoustic microscopy (SLAM), they proposed modifying the SLAM concept for multiple-frequency, multiple-projection, tomo-holographic capability.

If successful, they will produce a new composite microscope, the so-called scanning laser tomo-holographic acoustic microscope (SLaTHAM). They are interested in building a machine that will display on a computer monitor a live stream of pictures of three-dimensional microscopic objects. It will play like a movie showing any movement taking place in the object. Active in this effort have been M. Cywiak, L.R. Sahagún, R.A. Duarte, F. Mendoza-Santoyo, A. Meyyapan, and S. Isakson.

Ambitious? Yes, but not out of the question. It is safe to predict that if they don't succeed in doing it, some other group will.

Another exciting area of research involves the use of near-field techniques to improve resolution. This is important in all types of microscopy where good resolution is a must. Among the most potentially impressive of the microscopes are those that can scan and detect evanescent waves and by this means obtain super-resolution. Near-field approaches make this possible and are meaningful, not just in scanning acoustic microscopy, but also in scanning optical, scanning electron-beam, scanning tunneling, and scanning atomic force microscopy.

Conventional scanning acoustic microscopy (SAM) uses an ultrasonic lens that focuses an acoustic beam to a spot. The acoustic wavelength and the *f*-number of the lens determine the spot size according to Abbe's principle. In practice this limits the resolution to about 1 μm because of high absorption at high acoustic frequencies.

Jerzy Zieniuk and Antoni Latuszek proposed doing away with the lens and instead using a very small pin probe to guide the acoustic energy toward the microscopic object. With the object placed in the near field of the radiation from the pin, the pin diameter rather than the acoustic wavelength determines the resolution. The smaller the tip of the probe the better. This is a way to improve resolution (by using small tips) and at the same time maintain high object penetrability (by using low ultrasonic frequencies).

These ideas have been the starting point for the acoustic microscopy currently being researched in Germany's Fraunhofer Institute for Nondestructive Testing and elsewhere by such workers as U. Rabe, K. Janser, W. Arnold and E. Kester. So far the investigations have unearthed a variety of problems that must be solved before the work can be successful in producing a microscope competitive with the inventory of scanning near-field microscopes indicated above. For example, in a recent paper Dr. Rabe pointed out that high-resolution images of surfaces can indeed be generated but their quality depends upon discerning the elasticity of the surface under examination. Dr. Rabe and his colleagues are currently engaged in using the microscope itself to make the determination. I will go out on a limb to predict they will be successful in solving that and other problems, thus demonstrating the competitiveness of the ultrasonic pin approach to scanning near-field microscopy.

I am pleased to say that lack of space limits me to only one more prediction: that involving the use of 'limited diffraction beams' in a new pulse–echo imaging approach called the 'Fourier method'. One objective is to achieve a high frame rate of up to 3750 frames s^{-1} in producing two- and three-dimensional images and blood-flow vector measurements for biological soft tissues at a depth of 200 mm. This new method has shown theoretical promise for high frame rate multi-dimensional imaging of moving objects. In addition to medical imaging, the Fourier method could also be applied to remote sensing and underwater ultrasonic imaging.

What is a 'limited diffraction beam'? The concept has been under scrutiny for a long time starting with Lord

Rayleigh in 1897. Perhaps the best-known mathematical development appears in J.A. Stratton's 1941 book on *Electromagnetic Theory*. Theoretically such a beam, when produced by a proper radiator with an infinite aperture, can be diffractionless, i.e. travel forever without changing its transverse beam pattern. All actual apertures are finite and therefore all beams undergo some diffraction. In practice, however, beams can be produced with very 'limited diffraction' and hence with extremely large depth of field. The so-called X waves are in this category.

In the new Fourier method, a plane-wave pulse illuminates an object. The waves scattered from the object are received by an array transducer and weighted with limited diffraction beams to produce multiple A-lines simultaneously. From these A-lines, two-dimensional or three-dimensional images are constructed with Fourier and inverse Fourier transforms.

The researchers working in this area have included such stellar performers as J.-y. Lu, J.F. Greenleaf, M. Soumekh, H. Zou, T.K. Song, S. Holm, D. Ding, A. Sharrawi and M. Salomaa. It is easy to predict success in an endeavor with craftsmen such as these.

References

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