RESEARCH ACTIVITIES AND APPLICATION OF ULTRASONICS IN CHINA

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Abstract

During last 50 years there has been a large development of research and application of ultrasonics in China. This report gives a brief historical review and the general situation of the development in industrial, medical applications etc., and the state of affairs of the fundamental research.

Introduction

China is a large oriental country. The population now is 1300 million, the largest worldwide. China has a history of over 5000 years, one of the oldest in the world. There was a bright civilization in the ancient China, which includes science and technology in various fields. In the area of acoustics, Chinese people recognized the sound as a kind of wave as early as more than 2000 years ago. Based on the primary knowledge of acoustics, a lot of different kinds of Chinese traditional instrument were successfully manufactured, most of them are still used today and appreciated not only by Chinese people, but also by many foreign friends. It's also worth mentioning that the 12 equal temperatments were calculated by a prince of the Ming Dynasty around 400 years ago. Ancient Chinese people had quite good knowledge of room acoustics. In many ancient buildings we can see that the builders followed the correct acoustical principles. For example, it is very common to put big water vats under the stages as resonators to improve the sound quality of the singers. However, almost the whole Chinese ancient science was built exclusively on the basis of experience. People did try to explain what they observed and what they made. But most explanations were abstract and philosophical, a mixture of smart intuitions with hypothesis and guesses but lack of verifications. Since 17^{th} century, modern science characterized by systematic experiments and deduction on mathematics appeared in Europe. China, geographically very far from Europe, was unaware of the rapid developments.

In the 19 century, China began to find out that the outside world had been changed through the arriving of foreign fleets with big ships, powerful weapons and machines. Some sensitive countrymen recognized that China was lagging behind in science and technology. Many of them went abroad to learn the advanced science and technology. When they returned in China they did their best to develop modern education and scientific research. But they couldn't get notable achievements until the 1950s because of the continuous wars in this country. This is also the case of the ultrasonic research, till the 1950s, the whole field in China was nearly blank.

In 1955 Professor Chongfu Ying returned to China. Before he returned, he had received his Ph. D. degree in Brown University in 1951. Then he worked in the Metal Research Laboratory, Division of Applied Mathematics, Brown University till 1955 and among others published a paper on Journal of Applied Physics on scattering of ultrasonic wave in solid. It is the first paper on the issue and has been widely cited. In 1956 Professor Ying established a research group on ultrasonics in the Institute of Applied Physics, Chinese Academy of Sciences, the first one in China. Meanwhile he spread rigorously the knowledge and applications of ultrasonics in various occasions, attracting wide interests over the whole country. The first sets of ultrasonic detection equipment in China were built in a railroad factory in Beijing and in a shipyard in Shanghai. As the equipment was used for industrial testing, a couple of doctors in a hospital in Shanghai were interested in the method and start to try to use it in medical diagnosis. These events marked the beginning of the ultrasonic research and application in China, which has developed step by step later on.

I will present some aspects of the development. The presentation is definitely not complete because of the limitation of time and, more important, of the scope of my own knowledge.

Research on acoustic fields

In the Institute of Acoustics, Chinese Academy of Sciences (IACAS) a photoelastic visualization system was built in 1970-80s as shown in Figure 1 to make the propagation of the elastic pulse in transparent samples visible. The light souse is a YAG laser emitting light pulses of roughly 10 ns duration equipped with a crystal frequency converter. The time delay of the light pulse is adjustable continuously from 0.05 to few μs. The TV camera is connected image record devices which record various wave propagation processes.

An example of the scattering process of an incident longitudinal wave pulse in a glass sample by a cylindrical hole is given in Figure 2 in which a series of photoelastic photographs shows the time sequence of the incident and scattered waves. The incident pulse moves downward from the top and is reflected by the upper surface of the hole to produce cylindrical longitudinal and transverse waves until the incident wave advances to the point where the hole surface is tangent to the propagation direction of the incident wave. There the incident wave creeps around the hole wall into the geometrical shadow zone. On close examination it is found that the creeping longitudinal wave is always accompanied by a conjointly creeping transverse wave as shown in Figure 3.

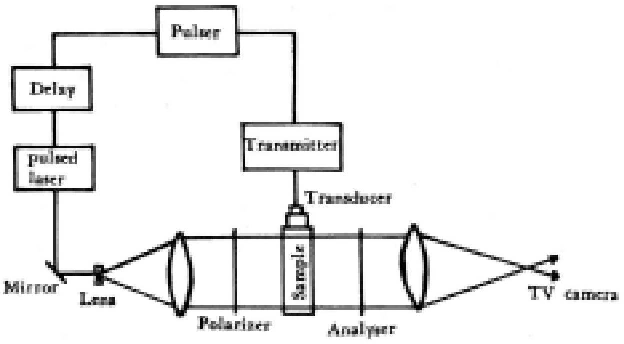

Figure 1: The stroboscopic photoelastic system

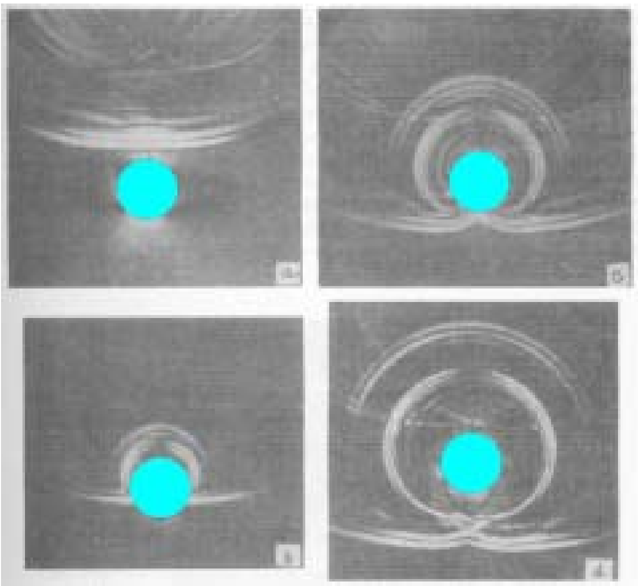

Figure 2: Scattering of longitudinal wave by a hole

As another example of novel observation, a surface wave pulse usually shows up a moving lobe structure pattern as shown in Figure 4, which is often found in the snapshots calculated by numerical methods recently.

In addition to this example, scatterings of ultrasonic pulses by boundary surfaces, corners, cracks have been photoelastically visualized.

In Tonji University, Shanghai and Nanjing University an laser ultrasonic experiment (Figure 5) and the finite element method are used to study the waves in an aluminum cylinder. Various waves are observed in the detected waveforms and correspond well with the Finite Element results in Figure 6 displaying the displacement fields in different instants. The letters P, S, H and R represent the longitudinal, transverse, head and Rayleigh waves, respectively.

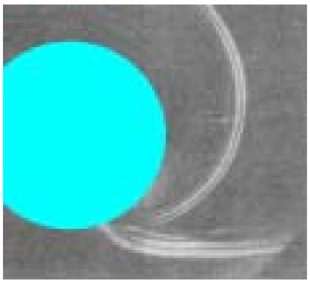

Figure 3: Creeping Waves

Figure 4: A surface pulse with lobe structure

Figure 5: Photoacoustic setup to study waves in a cylinder

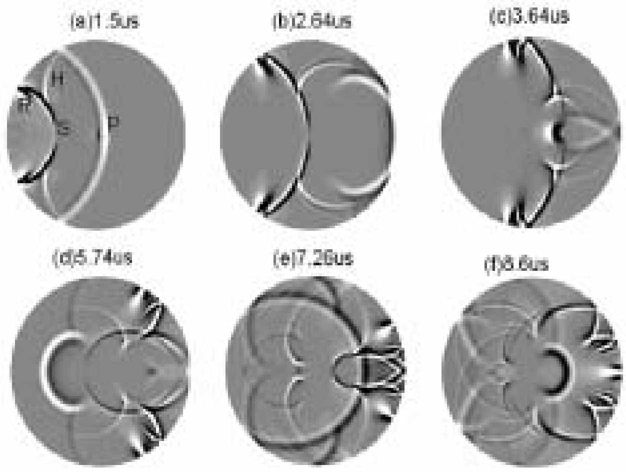

Figure 6: Acoustic field in solid cylinder by Finite Element method

These images clearly show that the longitudinal, shear, surface, and head waves all start at the line-source on the left, and separate when traveling further into the material because of different velocities. The head waves have curved wavefront, quite different from the linear wavefront in semi-infinite space.

Wave field can be calculated by using the discrete wavenumber(DW) method for regular geometry. As an example, the acoustic field generated by an eccentric source in borehole is calculated in IACAS. 4 snapshots at different times at a plane passing the borehole axis and the source are shown in Figure 7. The dark strips in the middle are borehole where the direct and reflected waves are represented by several arcs. On the two sides of the borehole is the formation where the longitudinal and transverse waves are represented by different arcs. Several straight lines inside and outside the borehole are various head waves.

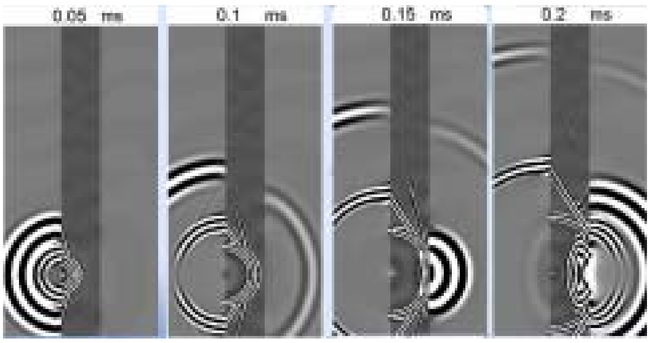

Figure 7: Eccentric borehole field by discrete wavenumber integration

Acoustic wave field in more complicated media, i.e., anisotropic and piezo-electric media is interesting because the surface acoustic wave (SAW) devices have been widely utilized in sensors, nondestructive evaluation and communication systems. In IACAS the exact vector theory of elastic wave diffraction fields generated by a finite-aperture surface source on piezoelectric crystal has been established, improving the conventional scalar angular spectrum theory and provide more accurate results. The generalized elastic wave fields generated by surface sources of piezoelectric crystal are deduced, which include three types of wave field: surface wave, bulk wave, and head wave. The result has been extended to the transient state. Based on the theory it is predicted and verified by experiment that there are electromagnetic acoustic head waves with planar wavefronts practically parallel to the surface as shown in Figure 8.

With the rapid development of the mobile communication system in recent years, the demand for SAW device with high operating frequencies is becoming increasingly important. Therefore, the high velocity SAW modes received great attention. In IACAS it is pointed out that the surface high velocity acoustic mode is a high velocity head wave for which the metallization of the surface has little effect on the velocity, different from that of the surface wave mode in piezoelectric substances as shown in Figure 9.

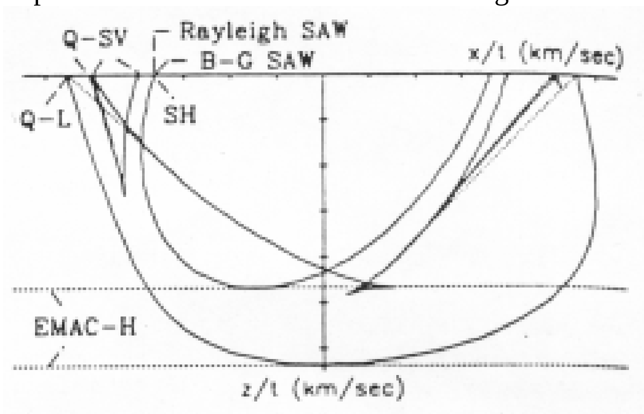

Figure 8: Wave front in Z-cut quartz excited by a surface line sources with electromagnetic acoustic head waves

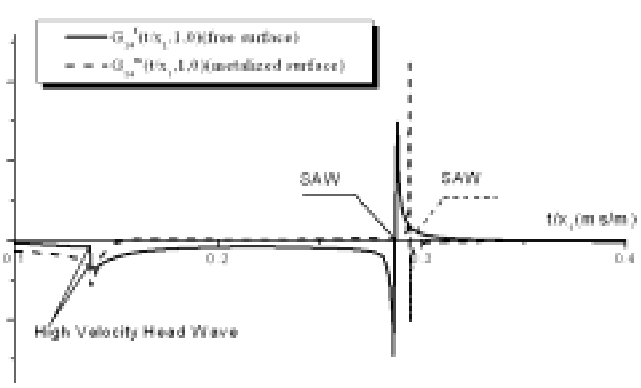

Figure 9: Excited waves on surface of YZ-$LiNbO_3$ by an impulse source.

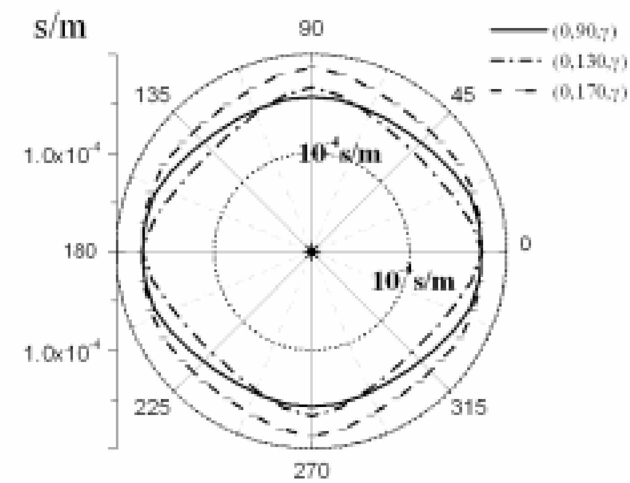

Figure 10: Slowness curve of QLLASAW on Y-rotated cut quartz

A group in Nanjing University studied Quasi-longitudinal leaky surface acoustic wave (QLLASAW) on Y-rotated cut quartz substrates and got the theoretical slowness curves of QLLSAW on Y rotated cut quartz substrates as shown in Figure 10. The phase velocity of QLLSAW on quartz substrates is from 5,000m/s to 7,100m/s, between the velocities of the fast shear wave and longitudinal wave. They find orientations with zero power flow angle (zero beam steering angle) and a low temperature coefficient.

Experimental study on a transient single bubble

Bubbles in fluid attract the attention of ultrasonic society recently because the cavitation plays important roles in the application of ultrasonic waves for many purposes. In IACAS experimental setup shown in Figure 11 is used to generate bubbles shown in Figure 12. The pressure signal received at the bottom of the glass tube and the lumination of the bubble are observed and recorded, which reveal some interesting features of the bubble during the procedure of the formation, growing, shrinking and crash.

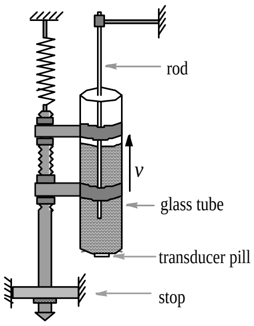

Figure 11: Experimental setup with seeded bubble nucleus for the generation of a transient single bubble

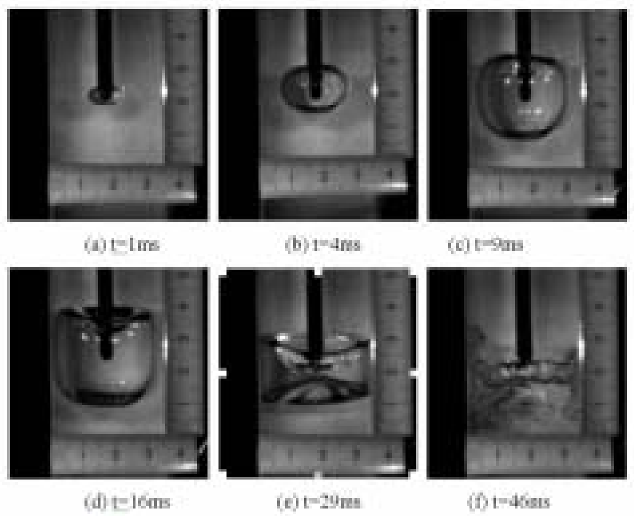

Figure 12: A developing single bubble in water inside a glass tube of interior diameter of 2.8 cm

Time Reversing

Ultrasonic Time Reversing has very unique advantages and has been used to focusing and imaging problems. In China several groups are interested in this direction. The focusing of ultrasonic beams by means of the time reversing technique in anisotropic medium is studied. The results in glass-reinforced epoxy and silicon in Figure 13 show a good effect similar to that observed in an isotropic medium.

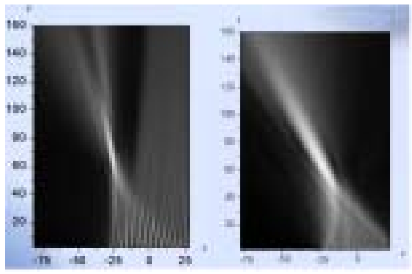

Figure 13: The focusing by means of the time reversing glass-reinforced epoxy (left) and silicon (right)

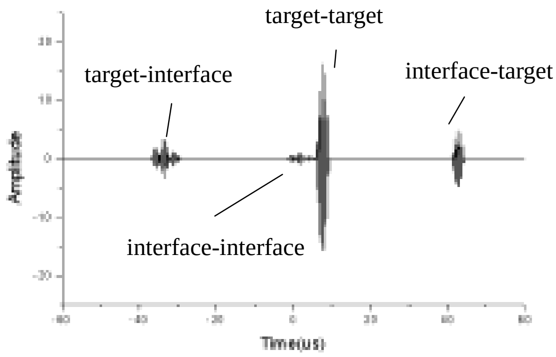

Figure 14: Detecting a target close to an interface by a modified TR

It is usually difficult to detect a target close to an interface in NDT problems. A modified Time Reversing method is proposed in IACAS to improve the situation. Using so called the Exchanging Element Time Reversal, i.e., different elements are used for the receiving before and after the time reversal, the coherent peak from the interface disappears and the target can be distinguished as shown in Figure 14.

Ultrasonics used for industrial NDT

Industrial Nondestructive Testing is one of the most important applications of ultrasonic waves. There has been rapid advance in the extensive use of NDT in almost all branches of the industry of China. There are tens of thousand technicians and workers engaged in applying this technique for various purposes. Many different kinds of NDE equipment are produced in China and dominate the Chinese market.

There are many research projects studying various NDE problems. One of them in IACAS is studying the ultrasonic evaluation of adhesive bonding for multilayered structure as shown in Figure 15. The waveforms from samples with the debonding flaws at different depths are recorded and analyzed. With the sophisticated signal processing, the appropriate characteristics can be extracted and the different debonding can be distinguished.

The dispersion curves of the Lamb wave in a multilayered plate are sensitive to the bonding quality at the inner interfaces as shown in figure 16 where experimental and theoretical dispersions in an aluminium-aluminium plate with welded or slip interfaces are compared. The dependence of the dispersive curves on the interface could be used to develop an technique of adhesive evaluation with high efficient.

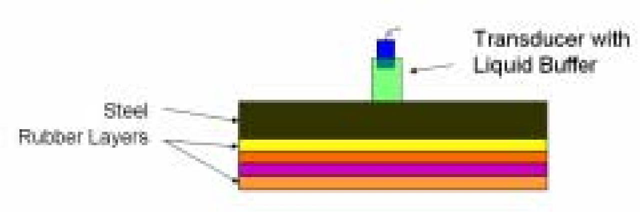

Figure 15: Ultrasonic evaluation of adhesive bonding for multilayered structure

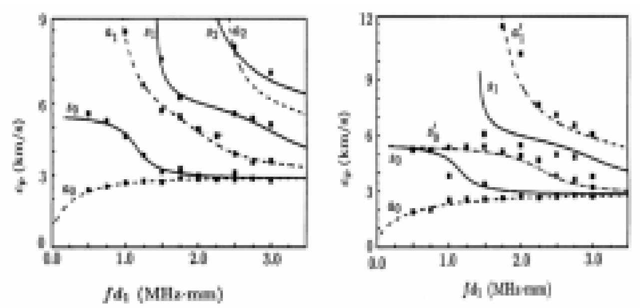

Figure 16: Experimental (dot) and theoretical (line) dispersions in an layered aluminium plate with welded (left) or slip (right) interfaces

Various ultrasonic flowmeters are developed and used in China. As an example a 4 path ultrasonic gas flowmeter is shown in Figure 17. Ultrasound can be used to measurement other physical quantity and the ultrasonic liquid concentration meter, pressure-difference meter and ultrasonic bolt stress meter were developed in Tongji University.

Scanning Electro-Acoustic Microscopy (SEAM)

Systems of scanning Electro-Acoustic Microscopy (SEAM) have been established in Tongji University, Nanjing University and Tsinghua University in Beijing. An electric beam is focused and scanning on the surface of a sample as shown in Figure 18. The elastic wave generated by the interaction between electrons and the sample is received by a PZT plate and is used to form an image. Different samples are used in these Laboratories and some of images are shown in Figure 19.

Figure 17: 4 path ultrasonic gas flowmeter

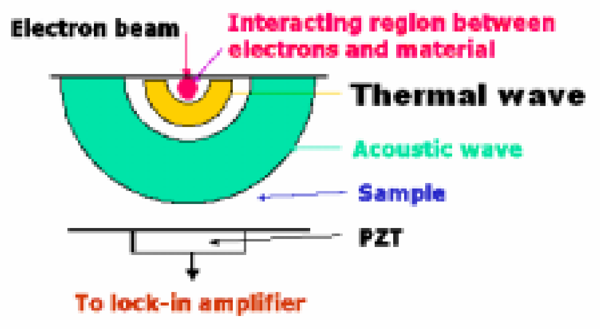

Figure 18: Principle of SEAM

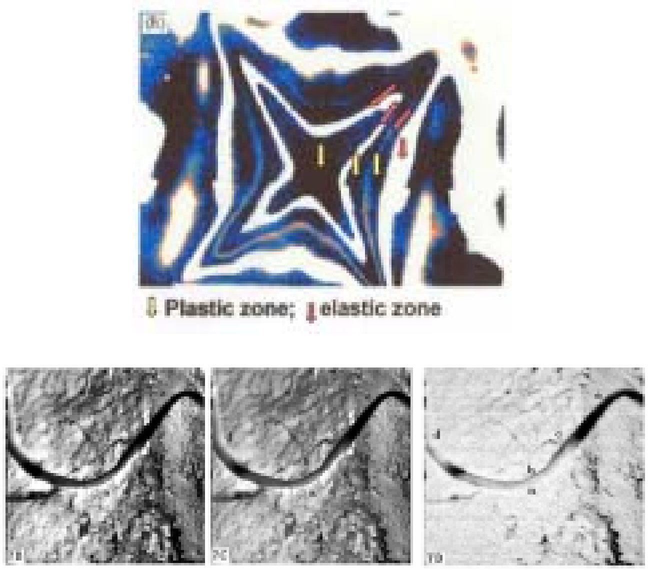

Figure 19: SEAM images of polycrystalline Al with residual stress (up) and of rabbit liver (down)

Transducers and devices

Transducers are the key part in all ultrasonic equipment. In China a large number of transducers are made every year. In IACAS both longitudinal and transverse wave transducers of the composite material are developed as shown in Figure 20. In Nanjing University the high frequency composite transducer up to 20MHz has been developed with the spectrum shown in Figure 21.

Piezoelectric tunable transducer was proposed in IACAS with the mechanical resonant frequency continually adjustable by changing an electric load reactance. As an example a piezoelectric transducer of longitudinal vibration tunable over 3/2 octaves is shown in Figure 22.

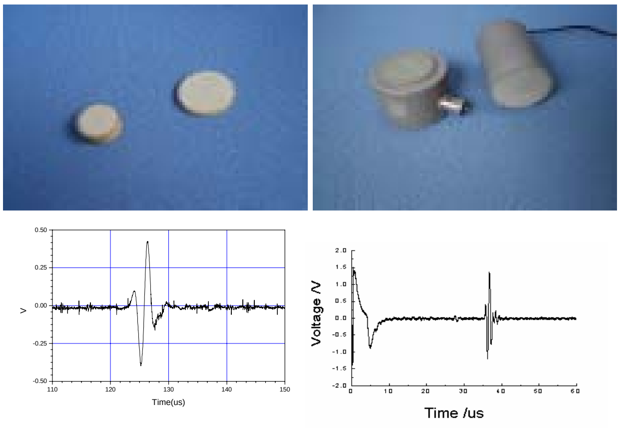

Figure 20: Composite plates, transducers and their waveforms

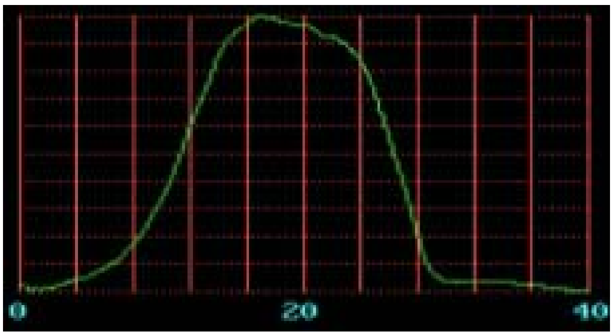

Figure 21: Spectrum of 20MHz transducer

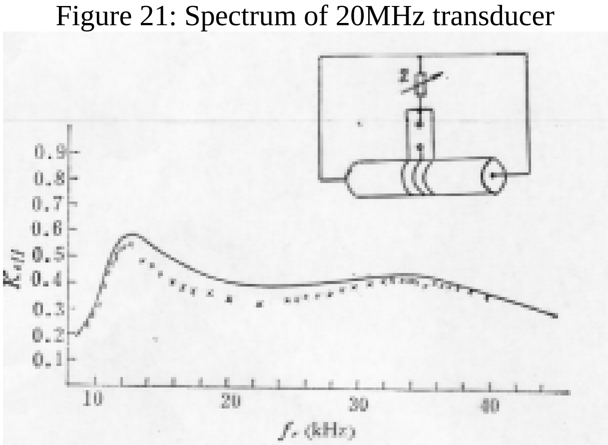

Figure 22: Effective coupling coefficient K_{eff} of the tunable transducer vs tuning frequency Theory(line), Experiment (cross)

Medical Ultrasonics

Ultrasonic diagnosis is widely used in Chinese hospitals. It is estimated that there are more than 100,000 doctors are qualified to use the ultrasonic diagnosis equipment. Now many kinds of the equipment and transducers are manufactured in China, some of them are shown in Figure 23. However, all of them belong to that of the middle or low levers. The high end machines used in Chinese hospitals are imported.

Figure 23: Some ultrasonic diagnosis equipment and transducers manufactured in China

More than 10 groups in universities and institutes of China are involved in various research programs of medical ultrasonics. Acoustic imaging systems of different principles were established in Nanjing University, such as the imaging with the nonlinear parameter B/A of the tissue, the imaging of transmission mode via a parametric array and reflection mode via second harmonics. An example of the nonlinear B/A imaging of a model is shown in Figure 24.

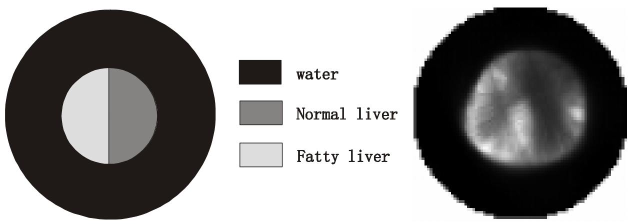

Figure 24: B/A imaging (right) of a model (left)

Recently many groups are interested in the ultrasound contrast agents(UCA). It is said the ultrasound contrast agents bring a new revolution in ultrasonic diagnosis after the introduction of the Color Doppler Flow Imaging. Different agents are designed, measured and tested. In Nanjing University the harmonic and sub harmonic components of the scattering signals of UCA are observed as in Figure 25. In Xi'an Jiaotong University the pictures of UCA under microscope are processed and the results are shown in Figure 26.

High Intensity Focused Ultrasound (HIFU)

HIFU is used to heat the specific tumour target resulting an temperature increasing beyond 65°C within seconds for non-invasively ablation of solid tumours. Thousands cases have been cured and the result is encouraging. HIFU systems are manufactured in several companies in China and used in many hospitals. Figure 27 shows a high intensity focused ultrasound system made in China.

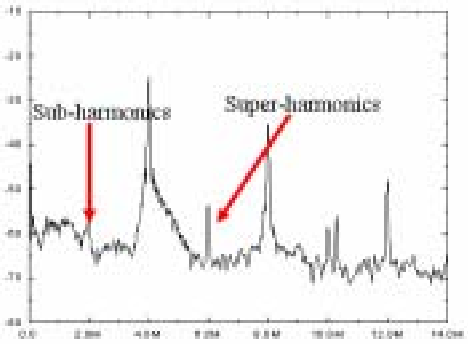

Figure 25: Harmonic and sub harmonic components of the scattering signals of UCA

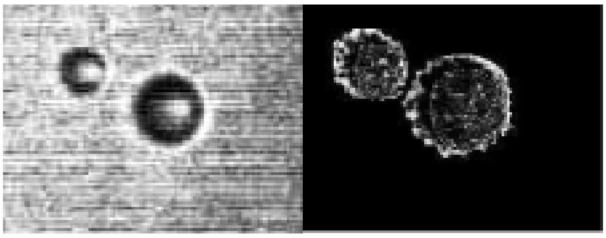

Figure 26: Microscope pictures of UCA (left) and strain distribution (right)

Figure 27: High intensity focused ultrasound system made in China

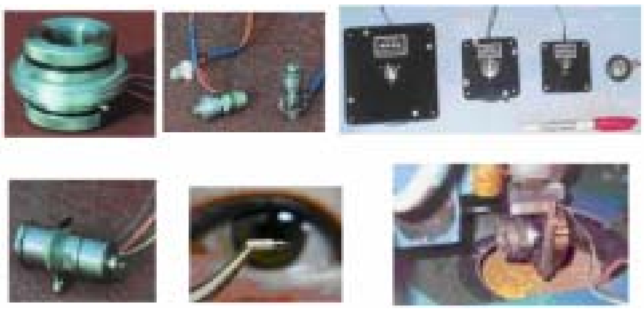

Figure 28: Some proto types of ultrasound motos made in China

High power ultrasonics and ultrasonic motors

Traditional high power ultrasonic systems are widely used in China for cleaning, washing, welding and processing. A new mechanism called as local resonance has been proposed to design ultrasonic driller. The frequency of the system is adjustable to match the changing of the frequency of the tool as it is wear out .

Ultrasonic motors are studied by many groups in China, and some proto types are shown in Figure 28.

There are tens of research groups and hundreds of people in China carrying out the ultrasonic research. Counting persons in industrial departments and hospitals applying ultrasound, the number definitely exceeds 200 000. This report does not give a complete outlook, but I hope it would give a general picture of the present status of Ultrasonics in China. The material reported here is based on what are available to myselfe, very likely I have left out some work of importance. Thanks are due to those ultrasonic fellow-workers at home who supplied me with these materials.