Proceedings of The Institute of Acoustics

Development of Measurement Standards and Techniques

Alison Livett

National Physical Laboratory, Teddington

An Ultrasonics Unit has been formed at the National Physical Laboratory to establish and maintain measurement standards, and to act as a focal point for the development of ultrasonic measurement practice in the UK. In this paper, the various techniques being developed and used for the determination of ultrasonic fields are reviewed.

There are a few points to be made at first to give some indication of the difference between the problems encountered in ultrasonics and in acoustics. The frequency of ultrasound used in medicine is typically 0.5 MHz to 15 MHz, and within this frequency range ultrasound does not propagate well through air. This is partly due to the poor efficiency of ultrasonic sources in coupling energy into a gas, and partly because of the attenuation of the air itself. Unfortunately, there is also at present no satisfactory means of characterising an ultrasonic field within a patient's body, and so measurements are carried out on the fields propagated by ultrasonic transducers into a water-filled test tank. Water is chosen because of the match of its acoustic impedance to that of tissue. This match ensures that the transducer emits approximately the same amount of energy into the water bath as it would into the human body. In water, medical ultrasonic wavelengths range from 3 mm. down to 0.1 mm., and with such short wavelengths certain specific difficulties are encountered. These occur mainly because source transducers and receivers with characteristic dimensions much less than a wavelength are just not feasible.

Medical ultrasonic transducers, then, consist in general of piezoelectric drive elements of several wavelengths across. The fields they produce are, in consequence, directional and contain a great deal of near-field interference structure. Such fields may of course be fully determined by measuring the temporal variation of field parameters, such as acoustic pressure or particle velocity, at all points in the beam, but for most practical purposes this is neither required, nor indeed is it strictly practicable. Instead, a number of other parameters are measured and used to describe the characteristics of the field as a whole. These are:

1. the total time-averaged power,
2. the spatial peak, temporal average intensity,
3. the peak acoustic pressure amplitude.

Firstly, let us consider the determination of the total output power from an ultrasonic transducer, which at the NPL is achieved by measurement of the radiation pressure. This is a force due to the momentum carried by a wave. Any object which absorbs or reflects an ultrasonic wave will change the momentum of the wave. This change of momentum produces a force on the object, known as the radiation pressure, and this can be measured and related to the total power in the ultrasonic beam. The ultrasonic equipment used in medical diagnosis, both pulse-echo and Doppler, has a total time-averaged power typically of 5 mW., and this produces a force of approximately 500 μg on a totally absorbing object. Powers used in physiotherapy machines typically give a force of 0.5 gm, and in general two different types of equipment are needed to cope with this large range of powers.

For diagnostic ultrasonic equipment, a sensitive radiation pressure balance has been built. This consists of a servocontrolled microbalance with a totally reflecting target suspended from one arm. The target is immersed in a water bath with a transducer at the bottom, and when this transducer is excited, the momentum of the ultrasonic beam produces a force on the target which changes its apparent weight. The change in weight is measured by the balance and can be related to the total time-averaged power from the transducer to an accuracy of a few percent. Eventually this balance will be used to calibrate standard transducers to provide stable sources of known ultrasonic power for calibration of field instruments.

For the power levels used in physiotherapy machines, a tethered float radiometer has been devised and built at the NPL. This consists of a reflecting target held in place with a water bath by three light silver chains linking the body of the target to the walls of the bath. Each of the chains hangs in a loop and the weight of chain supported by the target is just sufficient to balance out its buoyancy. The target sinks below the water surface and its position can be measured. An ultrasonic transducer is directed downwards towards the target, and the additional force exerted by the ultrasound is compensated by a downward movement of the target and a consequent redistribution of the load imposed by the chains. The target finds a new equilibrium position and the displacement of the target can be measured and related to the total time-averaged power from the transducer. This float radiometer can, in practice, measure physiotherapy power levels to an overall accuracy of ±10%.

These then are the methods used for measurement of total power, but to discover the way in which this total energy is carried by the beam, it is necessary to look at the spatial and temporal distribution of acoustic pressure in the ultrasonic field. One method is the use of an optical Schlieren system. As the ultrasound travels through the water, a refractive index gradient is associated with pressure variations in the ultrasonic beam, and if the beam is illuminated, the regions of different refractive index gradient appear lighter or darker than the background level of illumination. Hence an image of the ultrasonic wave is produced, and this Schlieren technique can be used to give qualitative information about the ultrasonic field. For a quantitative knowledge, however, it is necessary to insert small probes in the beam to sense a parameter such as acoustic pressure at each point. As mentioned earlier, the parameters of interest are the spatial peak, temporal average intensity which is related to the energy delivered to a particular region, and the peak acoustic pressure amplitude which may be important in pulsed fields. For diagnostic Doppler equipment, which uses continuous waves, the intensity is typically 10 mW/cm^2 with a peak pressure of 0.2 atm., while for pulse-echo equipment of a similar intensity the peak pressure may be 3 atm.

Conventional probes used for measuring acoustic pressure at a point consist of a small piezoelectric ceramic element mounted on the tip of a rod or cone. These probes are not absolute measurement devices and must be calibrated in terms of output voltage against applied acoustic pressure. One of the calibration procedures used at the NPL is a reciprocity technique which requires the measurement of electrical quantities only. It relies on the reciprocal behaviour of certain transducers with carefully determined beam characteristics. In such reciprocal transducers, the factor determining the front surface movement for a certain input current when the device is used as a source is directly related to that determining the voltage generated by an applied pressure when it is used as a receiver. A hydrophone may be then calibrated by noting its signal output when placed at a well defined point in the field generated by a reciprocal transducer.

Unfortunately, ceramic hydrophones have several disadvantages. Firstly, the impedance of the elements and their size means that they perturb the fields they are being used to measure, and, secondly, they exhibit internal reverberations and response characteristics that are highly frequency dependent. As the transverse dimensions of the ceramic are reduced to improve the directional characteristics of the hydrophone, the frequencies of the natural radial resonances of the element occur nearer the centre of the operational frequency band and tend to affect the frequency response of the device.

A different approach devised at the NPL is based on a piezoelectric plastic material, polyvinylidene fluoride (pvdf). The pvdf is used as a thin acoustically transparent membrane stretched over an annular frame large enough to allow the entire ultrasonic beam to pass through the central aperture. A small central region of the membrane is coated on both surfaces with metal electrodes and is polarised to induce piezoelectric properties only within that region. The device, therefore, may be regarded as a small sensing element, suspended freely in the ultrasonic field, which responds to local pressure fluctuations associated with the passage of ultrasonic waves. This detector offers a number of advantages over conventional ceramic hydrophones. Firstly, the pvdf can be fabricated as a film with thicknesses down to a few μm, giving a device so thin that it does not interfere with the ultrasonic field. Secondly, the frequencies of transverse or radial modes of the membrane are related to the diameter of the entire device rather than that of the active element alone, and will be well below the 0.5 MHz lower limit of interest. Further, since the acoustic impedance of pvdf is more closely matched to water than that of ceramic materials, the acoustic reflection coefficient at the surface of the membrane will be low and the device will only exhibit low Q resonance effects and hence will have a broad frequency response. The membrane hydrophones with a 1 mm. active element have a smooth frequency response which is flat to ±3 dB out to 100 MHz.

Looking to the future, a multielement membrane hydrophone is under development at the NPL. This may be able to provide quick and accurate profiles of the ultrasonic beam and prove to be a convenient field instrument. A new hydrophone calibration technique based on spectral analysis of nonlinear fields is also being investigated. These nonlinear fields have a spectrum which consists of harmonic components of the fundamental frequency, and the shape of the spectrum can be evaluated using spectral analysis techniques combined with a hydrophone of known frequency response. The characterised field can then be used to rapidly investigate the frequency response of other hydrophones.

In conclusion, these then are some of the techniques under development at the NPL both to provide primary standards for use in the laboratory itself, and to help to introduce new field instruments capable of simplifying everyday ultrasonic measurement and improving the accuracy available.