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A STRATEGY FOR THE DEVELOPMENT AND STANDARDISATION OF MEASUREMENT METHODS FOR HIGH POWER/CAVITATING ULTRASONIC FIELDS:

REVIEW OF HIGH POWER FIELD MEASUREMENT TECHNIQUES

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ABSTRACT

This report was compiled as part of a project to formulate a strategy for the development and standardisation of measurement methods for high power/cavitating ultrasonic fields. It reviews the scientific literature relating to various methods of measuring high power fields which have been developed for application in healthcare, sonochemistry and industrial ultrasonics, and compares these methods in terms of attributes such as spatial resolution, bandwidth and sensitivity.

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CONTENTS

1 INTRODUCTION

This report describes a literature review of high power field measurement techniques compiled as part of a six-month project for the DTI National Measurement System Policy Unit entitled **Study to Review Progress, Identify Measurement Methods and Address Implementation for Remote and Local Sensing Methods for the Measurement of High Power / Cavitating Ultrasonic Fields.** The review was undertaken during April-September 1996 and was carried out by the Centre for Ionising Radiation and Acoustics (CIRA) at the National Physical Laboratory (NPL). The objective of this report was to review the state of technical progress in measuring high power ultrasonic fields as revealed in the open scientific literature. The findings have been fed into a final project report[1] which provides recommendations on an implementation strategy for future developments in this area.

1.1 BACKGROUND

High power ultrasonic fields are used in a number of diverse application areas, which are described briefly in section 1.2. Measurement methods for these high power fields are important for reasons of safety, for example in monitoring output levels of ultrasonic lithotripters in medicine, and also in device and process monitoring, for example in ultrasonic cleaning. Currently, there are few well-documented, traceable measurement methods for high power ultrasonic fields.

Initially, the development of measurement techniques was driven by the medical applications of ultrasound, amid concerns over the safety of exposure levels from diagnostic and therapeutic equipment - devices which generally operate at acoustic frequencies in the megahertz range[2]. Standard techniques have been established for the measurement of low power ultrasound, centred on the medical field[3,4,5,6]. Indeed, declaration of the levels of the acoustic output parameters of medical equipment is now in itself a requirement[7]. In the high power arena, this applies specifically to lithotripters. Thus, there is an explicit need for standardised measurement techniques suitable for measuring the acoustic parameters of high power ultrasound fields, using calibrated instrumentation.

Extension of the standards infrastructure to include high power fields requires an initial assessment of current techniques, and an evaluation of their suitability for development as standard high power field characterisation methods. Reviews of measurement techniques aimed specifically at the medical field have been published[8,9], but there are comparatively few similar articles applicable to other applications[10].

Measurement of the output levels from medical devices is made easier by the fact that many systems operate in pulsed or toneburst modes. In interpreting measurements of medical fields, it can be assumed that free-field conditions apply. This is generally not the case for high power systems, which normally operate in continuous wave modes, and in which the environments are strongly reverberant. Increasingly, knowledge of the spatial dependence of these ultrasound fields is becoming more crucial. This is reflected not only in medical applications, where such concerns have been prevalent for some time, but also in applications such as ultrasonic cleaning, where some regions in a typical bath will clean better than others, and in sonochemistry, where knowledge of reaction locality will almost certainly lead to users and manufacturers being able to address the issue of scale-up on a more informed level.

1.2 APPLICATION AREAS

High power ultrasound is utilised in a broad range of applications, and the review of current field measurement techniques was undertaken in relation to these. Figure 1 presents an overview of these applications.

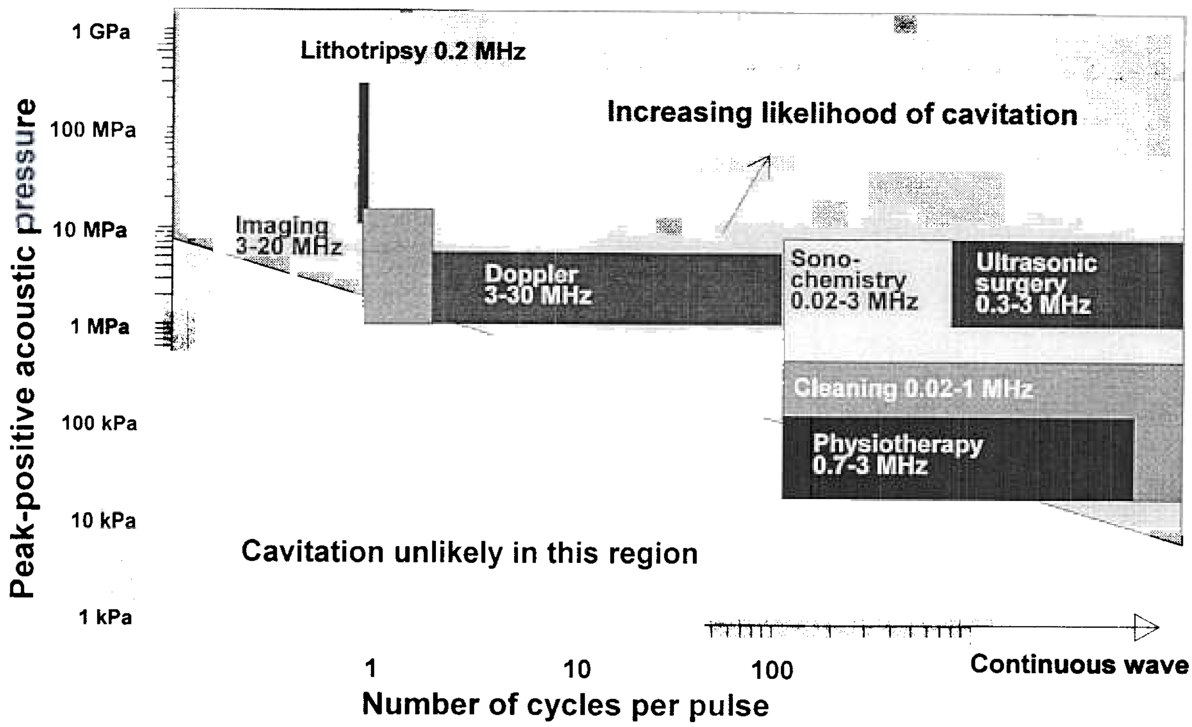

Figure 1: Applications of high power ultrasound fields

Defining the term "high power" is not trivial. It is easiest to consider high power fields as those which utilise cavitation to produce some desired effect, in other words, in this review, we are concerned with measurement techniques that can, or could be enhanced to, measure acoustic parameters in cavitating fields. In water, the threshold of cavitation can be as low as 1 bar (10^5 Pa) of excess pressure, a level well within the range of many ultrasound systems, although this threshold is dependent also on the frequency, the nature of excitation, and physical conditions such as temperature and dissolved gas content. Figure 1 illustrates a range of applications that either use or can generate cavitation. It would appear that high power fields can range in pressures from 10 kPa to over 100 MPa, depending on the frequency and the number of cycles per pulse.

High power ultrasound fields can be extremely difficult to characterise, often because of the cavitation events occurring. Not only can the cavitation activity cause damage to the measuring sensor being used, but the bubble populations generated can also scatter the acoustic signal produced by the source under investigation. Furthermore, the oscillating bubbles present will produce their own acoustic signatures, and resolving these from the signal produced by the source can be a complex process. The monitoring of cavitation itself is addressed in the accompanying literature review carried out by ISVR[11], and the techniques described will not be repeated here.

1.3 IMPORTANT ACOUSTIC PARAMETERS

This review deals with those measurement techniques which have been applied to the characterisation of the acoustic field properties of high power cavitating ultrasonic fields. It will be clear that, for a number of reasons, the review has leant heavily on the progress made in the area of medical ultrasonic field measurements. In this area, the high power cavitating fields encountered are those produced by extracorporeal shock-wave lithotripters along with some surgical devices and many of the techniques cited in the review have been drawn from these applications.

It is appropriate firstly to consider which specific acoustic field parameters are important in characterising a high power ultrasound system and in so doing we will ignore the influence of cavitation. Cavitation bubbles produced in the acoustic field will scatter the ultrasound and will themselves act as additional sources of sound, giving rise to a complex, time-dependent pressure distribution of the acoustic field. It is appropriate here to comment briefly on potential methods which may be of use in the suppression of cavitation, enabling quasi free-field characterisation of the field to be attempted. Viscous fluids or water of extremely high purity (thereby containing a low concentration of nucleation sites) could be used as propagation media of increased tensile strength. Alternatively, the application of high static pressures to the propagation medium may be used to increase its cavitation threshold. However they are made, such measurements undertaken in the absence of cavitation would provide information regarding the pressure distribution under specified test conditions, but these conditions (change of fluid, nucleation site concentration, application of increased pressure) may not relate simply to those experienced during a high power application.

Here, we will restrict ourselves to considering the acoustic properties of high power systems, such as ultrasonic cleaning baths or sonochemical reactors, which will normally produce a strongly reverberant environment. Ideally, we would wish to measure or monitor a quantity which is directly related to the process being facilitated by the ultrasound, so that the process may be manipulated or controlled in a precise fashion. In practice, this assumes a knowledge of the basic mechanisms surrounding the process and in most areas in which high power ultrasound is applied, this knowledge is still developing. In its absence, the most appropriate approach is to determine a range of acoustic field parameters which it is felt may influence or affect the process in question.

Principal amongst these must be the acoustic pressure generated in the field. Techniques used for determining pressure are given in Section 2 where the performance of various types of hydrophone is discussed. Additionally, Section 2.1.5 provides examples of high power ultrasound systems to which hydrophones have been applied. Under nonlinear conditions the peak rarefactional pressure may differ from the peak compressional pressure, but here we will assume that the pressures generated in the propagation medium are sufficiently low for nonlinearities to be ignored. We can associate this pressure p, with a particle velocity, u. The acoustic intensity, I, which gives the average rate of energy flow through unit area normal to the propagation direction, is given by

$$I = \langle p\,u \rangle_t = \frac{1}{t} \int p\,u\,dt$$

where <> signifies a time average and the limits of integration are taken over one acoustic cycle. The acoustic intensity is a vector quantity but in a plane progressive wave, where the pressure and particle velocity are in phase, the magnitude of the intensity is given by

$$I = \frac{p^2}{2\rho_o c}$$

where ρ_0 and c are the density and propagation velocity of ultrasound in the medium respectively. This relationship between pressure and intensity also holds in the transducer far field. In a reverberant field, typically encountered in ultrasonic cleaning and sonochemical applications, the pressure and intensity will vary strongly with position, due to the presence of standing waves set up within the enclosure. This standing wave pattern, and therefore the measurements of pressure or derived intensity, will be very sensitive to the effects of temperature and the liquid level of the cleaning bath. It is not clear whether a knowledge of the intensity vector is relevant in the characterisation of such systems. A more appropriate parameter for such systems may be the acoustic energy density. Comprised of both potential and kinetic energy contributions, the instantaneous acoustic energy density, ξ_i, is given by

$$\xi_i = \frac{\rho_o}{2}\left(u^2 + \frac{p^2}{\rho_o^2 c^2}\right)$$

The time-averaged energy-density, ξ, is derived by integrating this expression over one period of the wave. Again, assuming plane-wave conditions, the time-averaged energy density is given by $\xi = p^2/(2\rho_o c^2)$ or $\xi = I/c$. The discrete thermal probes dealt with in Section 4.1 respond to the time-averaged intensity flowing into the volume occupied by the thermal sensor and will therefore provide a measure of the energy density. This parameter will vary in space throughout the reverberant enclosure and a spatially-averaged parameter, derived from a sampling of the acoustic field at a number of field points, may provide a more robust measure of the acoustic energy being deposited in the tank. Such a device designed specifically for the characterisation of ultrasonic cleaning baths is described in Section 4.2.

For the reasons described above, the reverberant environment occurring in high power systems is very complex. The standing-wave pattern produced by an array of transducers in a cleaning bath , for example, can produce local variations in the acoustical parameters although frequency modulation is often used to smooth out the pressure distribution. Theoretical modelling of these systems is likely to be exceedingly complex for a number of reasons: the bubbles generated by cavitation will scatter the ultrasound, the water surface will distort under the influence of the acoustic radiation force and the vessel walls will undergo vibrations which are not solely piston-like but may include radial or surface-wave modes. Although it lies beyond the scope of the current project, the concepts used in airborne acoustics in the treatment of reverberation rooms may have some validity here. In particular, issues such as reverberation time, direct and reverberant sound fields may have some application. Additionally, the energy density may be determined from pressure measurements, provided that these are made in the far-field of the transducers, in a sufficient number of positions in the acoustic field.

2 HYDROPHONES

By definition, these are simply devices that measure acoustic pressure. Historically, hydrophone development was driven by the increasing need to be able to make quantitative assessments of the spatial and temporal characteristics of medical ultrasonic fields propagating into water. At the megahertz frequencies used in these applications, the need arose for broadband miniature sensors capable of accurate and reproducible measurements of such fields, fuelled by exposure concerns. Increasingly, however, the development of ever-more sophisticated diagnostic and therapeutic devices in the medical field has increased the demand for sensors of better spatial resolution, bandwidth and sensitivity, which are able to withstand increasingly hostile environments. This has led to the production of piezoelectric hydrophones with active elements as small as 40 μm and devices with membrane thicknesses of a few μm. The development of optical-based techniques for characterising ultrasonic fields has also increased, in the form of fibre-optic hydrophones, which can measure the acoustic pressure in a minimally-perturbing manner. In this section, the various designs of hydrophones available will be discussed in detail, following a general description of the requirements of such a device when applied to high power field characterisation.

2.1 PIEZOELECTRIC HYDROPHONES

Hydrophones of this type work according to the piezoelectric effect[12]: a change in the force on a material (in this case, due to the presence of an acoustic disturbance) produces a proportional change in the charge distribution within the material. In measurement practice, this charge is picked up by electrodes attached to surfaces of the piezoelectric element, and can then be amplified as a charge or as a voltage to produce a visual representation of the acoustic waveform, via a signal-processing oscilloscope. The implementation of this effect in the form of a device to assess the acoustic pressure in the field of an ultrasonic source is by no means straightforward. There are a number of important factors to consider in hydrophone design. The device should be non-perturbing: for example in a cleaning bath, we do not want to alter the standing wave pattern established. The errors due to spatial averaging which can occur when measuring medical fields of frequencies of a few megahertz are of less concern in most high power industrial applications, where devices operating at frequencies of 20 kHz produce ultrasound with a wavelength of approximately 7.5 cm. In addition, particularly for the measurement of medical fields, the device needs to have a uniform response over a wide frequency range, yet still be sensitive enough to produce a reasonable signal level that increases linearly with acoustic pressure. Further, it must be robust and rugged enough to withstand the sometimes hostile fields produced by high power ultrasonic equipment.

Robustness is perhaps the most relevant to high power ultrasound applications. By their very nature, many hydrophonic devices can be quite delicate and fragile as designs reach new levels of spatial resolution and non-invasiveness, with their susceptibility to cavitation damage around the active element being of concern. In part, this explains the comparative lack of literature available on the use of hydrophones in measuring the acoustic fields generated by high power ultrasound devices, with the exception of measurements made in the medical field, where concerns over safety have driven the development of accurate and robust devices (at the expense of performance, to a certain extent) which have been used in the characterisation of lithotripter fields.

2.1.1 Needle devices

Piezoelectric ceramics have been widely used in the development of hydrophones, and most designs using materials of this type consist of a disc-shaped active element supported at the tip of a needle-like structure which is made from some acoustically-absorbing material. The element and absorbing material are then housed in some form of supporting tube[13,14]. A schematic representation of such a device is shown in Figure 2.

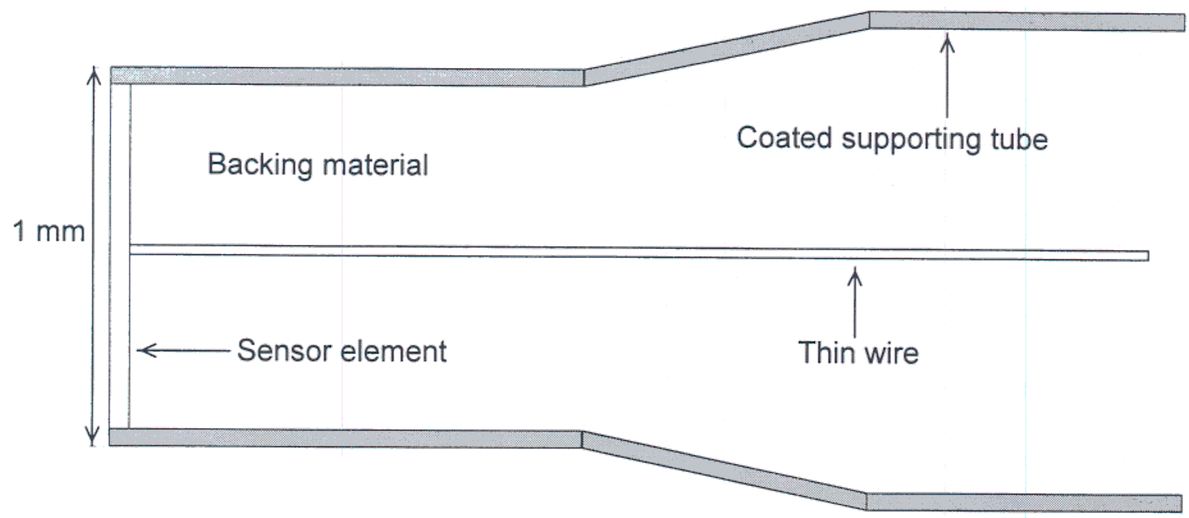

Figure 2: Schematic representation of ceramic needle-type hydrophone

Needle-type ceramic probes can be fairly robust devices, so are appropriate for the measurement of high power fields, and are usually of high sensitivity. However, they can suffer from unpredictable structure both in their frequency and directional responses due to radial resonance modes, reflections and mode conversions in the active element and backing material. The high characteristic acoustic impedance of ceramic materials (when compared to water) means that they perturb the field being measured. Typically, hydrophones of this type are constructed with active elements of diameter 0.4-0.6 mm, values which are much less than the wavelength at 40 kHz.

Closer characteristic acoustic impedance matching between the sensor element and water may be achieved through the use of the piezoelectric polymer polyvinylidene fluoride (PVDF). PVDF is also flexible and resistant to chemical attack. Using the type of construction employed in the ceramic needle probe, hydrophones have been designed using a PVDF active element[15,16]. Figure 3 shows such a design. The problems of irregular frequency responses when using ceramic piezoelectric materials noted above are reduced when using PVDF, but radial resonances are still of concern. In addition, the contact between the active element and the connecting thin wire can deteriorate over time, and like the ceramic needle-type hydrophone described above, this can lead to instability.

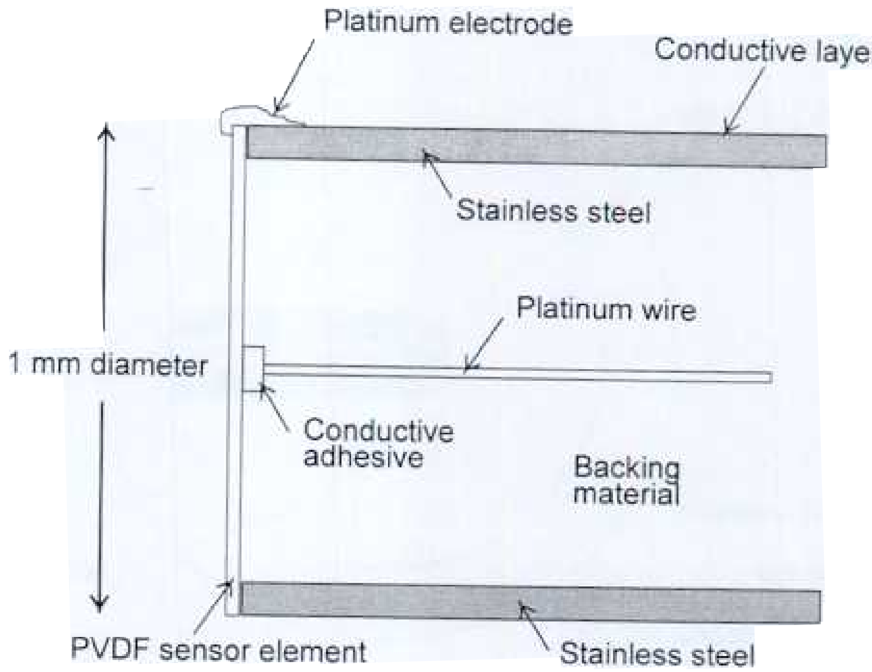

Figure 3: Schematic construction of PVDF needle-type hydrophone

2.1.2 Membrane devices

A further design of hydrophone has been produced, which has largely solved the problems encountered in using needle devices. This design is the membrane hydrophone[17], and it is now the accepted "gold-standard" world-wide device for making absolute, traceable measurements of acoustic pressure distribution in medical ultrasonic fields. It comprises a large sheet of PVDF in the form of a thin film, with gold or chromium electrodes vacuum-deposited on the surface, stretched across an annular frame. Metal film leads are evaporated onto both sides of the membrane, and the small overlap region formed determines the active area of the device. The majority of device developments were carried out in the early 1980's[18,19]. Modern manufacturing techniques can produce devices with active elements of 40 μm diameter, with bandwidths up to 150 MHz. Figure 4 depicts a typical coplanar design.

The characteristic acoustic impedance of PVDF is well matched to that of water and therefore, provided the membrane is thin, membrane hydrophones have the advantage of causing minimal disturbance to the acoustic field, especially as the ultrasonic beam generally passes through the aperture of the supporting ring. Also, the frequency response of membrane devices tends to be smooth in the megahertz frequency range. Membrane hydrophones find their use almost exclusively in the characterisation of medical fields below the threshold of cavitation, and are frequently used in degassed water to minimise the risk of cavitation occurring (for example, in physiotherapy fields). Some authors have used them in assessing the fields generated by lithotripters, fields in which peak-compressional pressures can reach in excess of 70 MPa[20]. PVDF would appear to be linear in its piezoelectric properties up to these levels[21]. However, when characterising lithotripter fields, membrane hydrophones may be susceptible to cavitation induced damage. The gold electrodes attached to the PVDF membrane can become locally eroded, even though the polymer itself is undamaged, and the sensitivity of the hydrophone can then decrease with continued exposure to lithotripter shock pulses. Bilaminar membrane hydrophones used in lithotripter measurements can suffer from delamination damage.

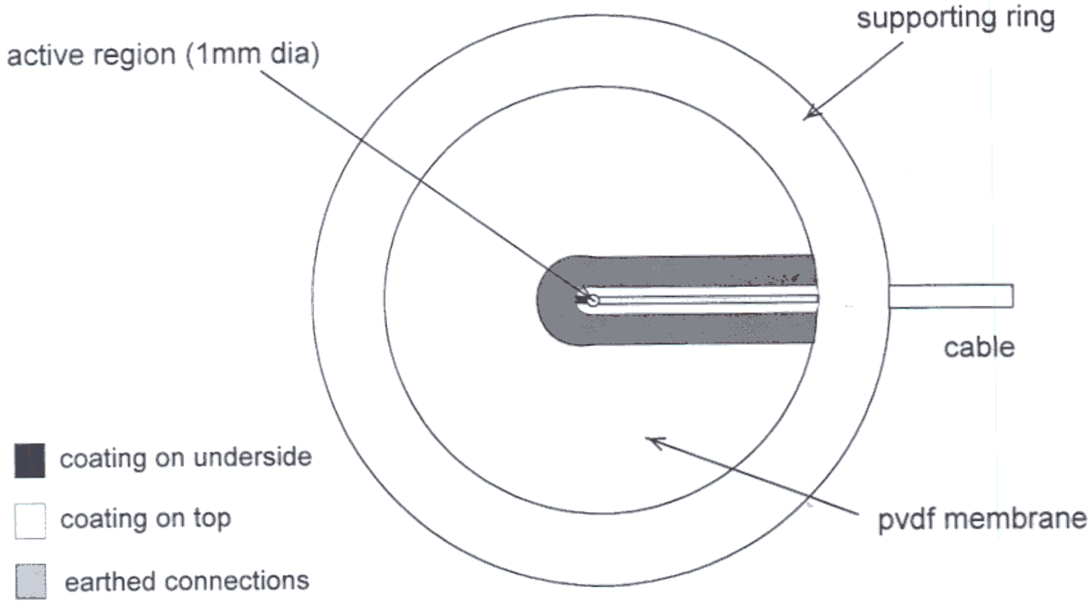

Figure 4: Schematic diagram of a coplanar membrane hydrophone

The application of membrane hydrophones to measurements of high power ultrasound fields has been limited to measurements of medical fields only, and even these have demonstrated problems with fragility[20]. Some needle-type probes have also been used in the characterisation of lithotripter fields[22], and generally this has been the limit of the extent of measurements using calibrated devices.

The need to make measurements of lithotripter field parameters, specifically of the peak-rarefactional pressure amplitude, coupled to the limitations shown when using conventional hydrophones has led to several variants on the conventional piezoelectric hydrophone theme[23,24]. Further, capacitance hydrophones have been applied to such fields[25]. An objective assessment of the desirable qualities of a piezoelectric hydrophone designed to measure lithotripter fields has been published, along with some results from a prototype device[26]. Two specific devices are covered in sections 2.1.3-2.1.4 below.

2.1.3 Liquid electrode hydrophone

Cathignol[23] has developed a membrane-style hydrophone applicable specifically to lithotripter measurements. The design is similar in some respects to a previously described hydrophone[27], but differs in that the electrodes are connected to the active element via an electrolyte rather than a dielectric liquid medium. A schematic cross-section of the device is shown in Figure 5.

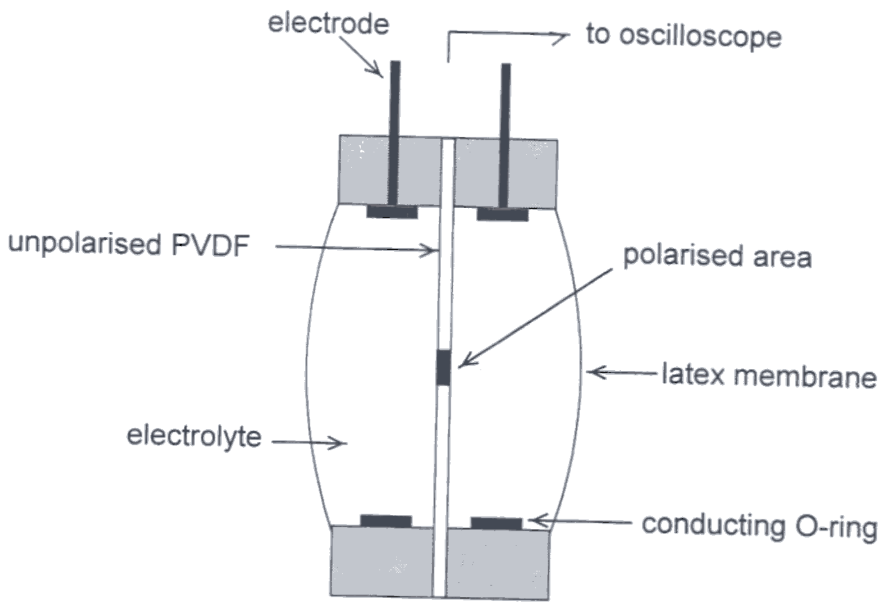

Figure 5: Schematic diagram of liquid electrode hydrophone

The device works by the piezoelectric effect, as described above. However, the effect of the charge distribution created by the impinging ultrasonic wave is transferred to the two metal electrodes via the electrolyte, rather than exposing the fragile electrodes themselves to the hostile field directly. The author constructed the device from a PVDF film of thickness 9 μm, with an active element diameter of 1 mm. This was calibrated against a conventional membrane hydrophone and shown to have a sensitivity of 12 mV/MPa over a bandwidth of 20 MHz. More importantly, it was able to stand in excess of 10^5 shock pulses of 30 MPa pressure amplitude without any significant decrease in sensitivity. The device is not as sensitive as a conventional membrane hydrophone (a similar coplanar device with a 1 mm diameter active element would have a sensitivity of around 70 mV/MPa, a factor of 6 higher), and may not have the temporal response. It is undoubtedly useful, however, for the assessment of lithotripter fields. A miniature device, based on a similar liquid electrode mode of operation has also been developed[28].

2.1.4 Reflector-style hydrophone

Bedi and Selfridge[24] have published details of another hydrophone variant developed specifically for measuring the output from lithotripter fields. Rather than using a polymer, they have reverted to manufacturing the device with a ceramic piezoelectric (lead titanate) active element backed by a matched acoustic impedance. This has been shown to undergo no significant change in sensitivity after 5000 shocks of acoustic pressures in excess of 100 MPa. In addition, the device is able to faithfully reproduce rarefactional pressures. The effect of the matched impedance is to *reflect* the incoming wave, rather than be acoustically transparent, as is the case for membrane hydrophones. Potentially, this mechanism can be damaging to the device, because if the reflection occurs at a boundary with an acoustic impedance less than that of water, an incident compressional pulse will be inverted to a rarefactional pulse, instantly causing cavitation adjacent to the surface. The matching layer is hence designed to prevent this occurring. In comparison with a conventional calibrated membrane hydrophone (the sensitivity of which was determined at low power levels), excellent agreement was seen in the peak-compressional and peak rarefactional pressures indicated by the two devices. In addition, the ceramic design did not suffer from the characteristic resonances seen in the response of a conventional membrane hydrophone (associated with the thickness response of the active element and cable resonances). The use of a ceramic active element also meant that the device had a higher sensitivity than that of a conventional membrane device with a similar (1 mm) active element size.

2.1.5 The application of hydrophones to the characterisation of high power systems

The application of hydrophones used in the medical field to many high power applications may be limited by their bandwidth, with lower cut-off frequencies typically being at hundreds of kHz, outside the 20 kHz operating frequencies of many sonochemistry and cleaning applications. Recent work has produced two miniature ceramic devices that claim to overcome this barrier, and also be resistant to the extreme conditions produced by strongly cavitating fields[29]. The construction of these devices is similar to that shown in Figure 2, comprising a lead zirconate titanate crystal supported on a cylindrical body. To reduce the influence of resonances on the device output, the active element was embedded in a silicone rubber and cork mixture, effectively decoupling the crystal from any tube wall vibrations. In addition, the active element was coated with a thin layer of polymer resin for protection. The hydrophone also includes an integral amplifier, producing a uniform gain over a frequency range from 10 kHz to over 100 kHz. In evaluation, the devices showed a flat frequency response up to 150 kHz, and sensitivities of a few mV/Pa. They appeared to produce a stable output over a 100 hour period of testing in a strongly cavitating environment.

Perhaps more suitable for application to the measurement of acoustic parameters at lower frequencies are hydrophones commonly used in underwater applications. These generally consist of a piezoelectric ceramic active element mounted inside a specialised rubber surround, which serves to match the acoustic properties of the sensor to the water. Devices of this type usually approach uniformity in their directional response, as at low frequencies, the element dimensions tend to be less than one-tenth of the acoustic wavelength. In comparison to the membrane and needle devices described above, the bandwidth of underwater hydrophones extends to the tens of kHz range. Use of hydrophones of this type in measurements of high power devices has not been widely reported, although a recent paper described such a device being used for measurements on an ultrasonic surgical instrument.[30]

Ultrasonic surgical instruments, used in dental descaling treatment, tissue fragmentation, phacoemulsification and other similar processes also fall into the category of "intentionally cavitating" devices. There is still a degree of uncertainty over the mechanism by which they operate, be it through cavitation, a hammer action, or perhaps a combination of these and other effects. Instruments of this type are usually characterised in terms of the vibration amplitude of the tip[31,32,33], but the link between this and the action of the devices is still uncertain. A paper cited above[28] demonstrated some attempts to characterise the acoustic field produced using two hydrophones: one to measure the acoustic signal directly at frequencies below 100 kHz, and another to quantify the "cavitation energy" over a wider bandwidth. Such acoustic emission techniques for monitoring cavitation can be found in the ISVR report[11].

2.2 FIBRE-OPTIC HYDROPHONES

In making measurements of high power ultrasound fields, the ability of the device to withstand the extremes of conditions produced by the field is of concern. A means to overcome this difficulty is to measure the field parameters using a device with a replaceable tip. Also, with uncertainties over the degree of field perturbation caused by piezoelectric devices, and the difficulties associated with manufacturing sensors with small active elements and usable sensitivities, there exists a need to investigate alternative measurement techniques or devices. These problems can be overcome to some extent by using fibre-optic techniques.

The compressive and rarefactive regions in an ultrasonic wave result in local changes of the refractive index of the transmitting medium. Due to the speed of light being much greater than the speed of sound, these regions of pressure maxima and minima appear stationary to an incident light beam. The ultrasound behaves as a phase grating, and using a photodetector and lens (or optical fibre) arrangement, information about the acoustic beam can then be derived from the resultant diffraction pattern[34,35,36,37]. The use of an optical fibre to measure an acoustic signal was first demonstrated by Bucaro et al[38].

A comprehensive demonstration of this form of optical hydrophone is given by Wu et al[39]. The device is based upon a two-fibre sensor, with the incident light beam being diffracted by the acoustic signal propagating at right angles to it. Using the principle of Raman-Nath light diffraction, the amplitude and phase information from the acoustic signal can be reconstructed from the light intensity levels produced by the receiving fibre, assuming the number of harmonic terms produced by the diffraction is restricted. The device showed good agreement with results obtained from a piezoelectric needle probe positioned at the same point in the field. The frequency response was reasonably flat over the range 1-15 MHz: however, this is limited only by the wavelength of the light beam used (0.6328 μm), the bandwidth of the photodetector, the interaction region and the properties of this medium. The authors concluded that the device was suitable for measurements of both continuous wave and pulse signals, and has potentially a high spatial resolution, comparable to the core diameter of the optical fibre used.

In further studies using the same device[40], a range of spectral and spatial measurements of focused and unfocused transducers of frequencies up to 20 MHz were carried out, again showing reasonable agreement with data from a 0.5 mm diameter PVDF needle hydrophone. However, in both sets of studies, the system suffered from electrical noise, and the fibre optic sensor had a sensitivity some 20 dB lower than that of the PVDF probe.

A further development of optical sensor has been demonstrated by Huber et al., in their so-called laseroptic hydrophone[41]. In this case, light from a laserdiode is coupled to a quartz glass optical fibre of a 50 μm core diameter, and the end placed into the acoustic propagation medium. Some of the emitted light is reflected back into the fibre, depending on the ratio of the refractive indices of the medium and the fibre. This reflected light can then be detected using a y-coupler and photodiode arrangement. The local density of the water, and hence its refractive index is increased in the compressional phase, thereby reducing the difference between the respective refractive indices, and the reflectivity. The reverse occurs in the rarefactional phase, producing a time-varying signal at the photodiode. The laseroptic probe was independently calibrated using a range of liquids of known refractive indices. Good agreement was seen between the laseroptic probe, a needle hydrophone and a capacitively-coupled membrane hydrophone in the acoustic pressure values derived.

Interestingly, the laseroptic hydrophone appeared to provide information on cavitation occurring close to the end of the fibre, shown by the photodetector as sharp peaks, due to the marked difference in the refractive indices of water and air. A proportional correlation was seen between the negative pressure amplitudes measured and the duration of the cavitation signal detected. It would seem, in this case, that the probe could be used to monitor simultaneously both acoustic pressure and cavitation. The device demonstrated would appear to provide useful information on the lithotripter fields measured. However, it still suffers from the lack of sensitivity prevalent in most optical techniques, again being 20 dB lower than the piezoelectric devices tested.

A version of the type of sensor demonstrated by Huber et al was also developed by Staudenraus and Eisenmenger[42]. Using the same principles of an acoustic pressure change inducing a variation in the optical reflectance at the boundary between the fibre end and the medium, the authors constructed a more sophisticated variant, incorporating a noise detector, producing a clean waveform. The device was shown to have a bandwidth of 20 MHz, and a spatial resolution of 0.1 mm. Again, the authors tested various aspects of its performance against several different piezoelectric hydrophones: a PVDF needle probe, a PVDF membrane hydrophone and a capacitively coupled PVDF device[27]. The limitations in measuring rarefactional pressures with conventional PVDF hydrophones (due to the low cavitation threshold at the metallised surface) were seen in the comparison, with the fibre-optic probe providing the lowest values of peak rarefactional pressure (-15 MPa) seen. The PVDF devices showed that the rarefactional pressure responses were truncated by cavitation, only reaching levels of around -7 MPa. The fibre-optic probe was again shown to be less sensitive than the PVDF devices. However, this problem was overcome somewhat by the application of a thin layer of optically clear silicone rubber over the end of the fibre, which produced a seven-fold increase in sensitivity. Recent measurements using a fibre-optic hydrophone of this type have shown an ability to measure peak rarefactional pressures as low as -25 MPa[43].

The principle of Fabry-Perot interferometry has been used in the development of a different type of fibre-optic probe[44]. The device described consists of a optical fibre which has a thin polymer film mounted at the end. The presence of an ultrasonic field induces changes in the thickness of this element, which are then picked up by an interrogating interferometer. Such a design has been shown to be of wide bandwidth and of excellent spatial resolution, with a sensitivity similar to a PVDF membrane hydrophone; indeed performance evaluation in comparison to membrane hydrophones has shown excellent agreement when used in lithotripter fields. The device has its main application in this area, being of sufficiently small dimensions to be used *in-vivo*. It is thought that information on cavitation activity at the focus of an extracorporeal shock wave lithotripter can also be obtained from the design.

An interesting method is again based on interferometry[45], in which the presence of an acoustic signal causes measurable changes in the refractive index. In this case, the authors investigated these refractive changes in a solid material, using optical fibres embedded in sample materials of polyethylene and graphite composite. Using a PZT transducer for their ultrasonic source, they were able to detect signals over a 100 kHz to 5 MHz bandwidth. The technique would perhaps have limited application in "real systems", although it may be applicable to ultrasonic welding, where currently, acoustic measurements are rarely performed.

The use of optical techniques in the characterisation of high power ultrasonic fields has currently been limited to making measurements on medical devices. Fibre optic hydrophones can be calibrated against piezoelectric devices at low acoustic pressures to yield absolute information, and their use would seem to be gaining increasing recognition as a suitable means of evaluating high power field characteristics. Further, an optical technique could be used to monitor acoustic pressure and cavitation emissions simultaneously, with the required signal being achieved by signal filtering techniques. Sonoluminescence could even be monitored by fibre-optic probes, if the signal-to-noise ratio was adequate.

3 OPTICAL INTERFEROMETRY

The use of optical techniques is not restricted solely to hydrophone probe-like devices. The local changes of particle position in a medium caused by the progression of an acoustic wave can cause a displacement of a surface or membrane, which can then be interrogated by an optical beam. Such a technique allows remote monitoring of field parameters. The displacement produced by continuous plane progressive waves of intensity 100 mW cm^{-2} at 5 MHz is around 1 nm, and greater displacements are seen at lower frequencies. Using a moving membrane or pellicle, a heterodyne interferometer can be used to assess the exact displacement, which is proportional to the acoustic pressure amplitude at that point (assuming plane wave propagation). This technique has been demonstrated by Royer et al[46]. The method demonstrated involved the probing of a field using a reference beam and a probe beam, focused onto a gold reflecting coating on a thin pellicle immersed in water. The technique exhibited a bandwidth of 20 MHz, with a spatial resolution better than 0.1 mm, corresponding to a minimum detectable time-averaged acoustic energy of $2\mu J/m^2$. An interferometer of this type has been adapted for use as a primary standard instrument for the calibration of hydrophones[47]. The Michelson interferometry principle has also been extended recently to a fibre-optic based sensor[48].

Recent work directed specifically at the assessment of lithotripter fields has produced a variant of the Michelson interferometer with a long-path-difference geometry, to measure the *velocity* of a pellicle placed in the acoustic beam[49]. Again, this parameter can be used to derive the absolute acoustic pressure. Extracorporeal shockwave lithotripters can produce particle velocities in the range 1-100 m s^{-1}, and in the cited research, the velocity of an acoustically transparent but optically reflecting target located in the field of a shockwave source was evaluated with an interrogating single-mode laser beam. Preliminary trials have shown that the system has a bandwidth of 100 MHz.

4 THERMAL METHODS

As ultrasound propagates through a medium, its amplitude decays due to the attenuating nature of the medium. This is due to absorption and scattering effects. In a homogeneous material, where energy losses due to scattering may be considered negligible, the absorption is attributable to thermal conductivity, viscous effects and other molecular processes. This energy transfer results in a temperature rise in the medium, which can be used to provide information about the acoustic field. Two independent classes of measurement technique can be derived from this effect, one of bulk techniques, the other discrete.

4.1 DISCRETE THERMAL METHODS - SINGLE ELEMENT PROBES

Almost certainly, the first type of sensor that was developed and used to yield information on ultrasonic field distributions was based on a thermal detection method. The original theory and experimental evaluation of this type of probe was first carried out in the 1950s[50].

Simple and inexpensive in construction, discrete thermal probes are based on thermocouples or thermistors, usually encased in an acoustically-absorbing material, preferably with a similar acoustic impedance to that of water. When placed in an ultrasonic field, temperature rises are produced in the surrounding material by the absorption of ultrasound, which causes a change in the electrical output of the thermal device. From the literature, the initial rate of temperature rise in the absorbing medium, during the first few tenths of a second after the insonating field is activated, is proportional to the acoustic intensity[51], assuming that the heat losses are small over this short time period. Figure 6 illustrates a typical time response of a discrete thermal sensor.

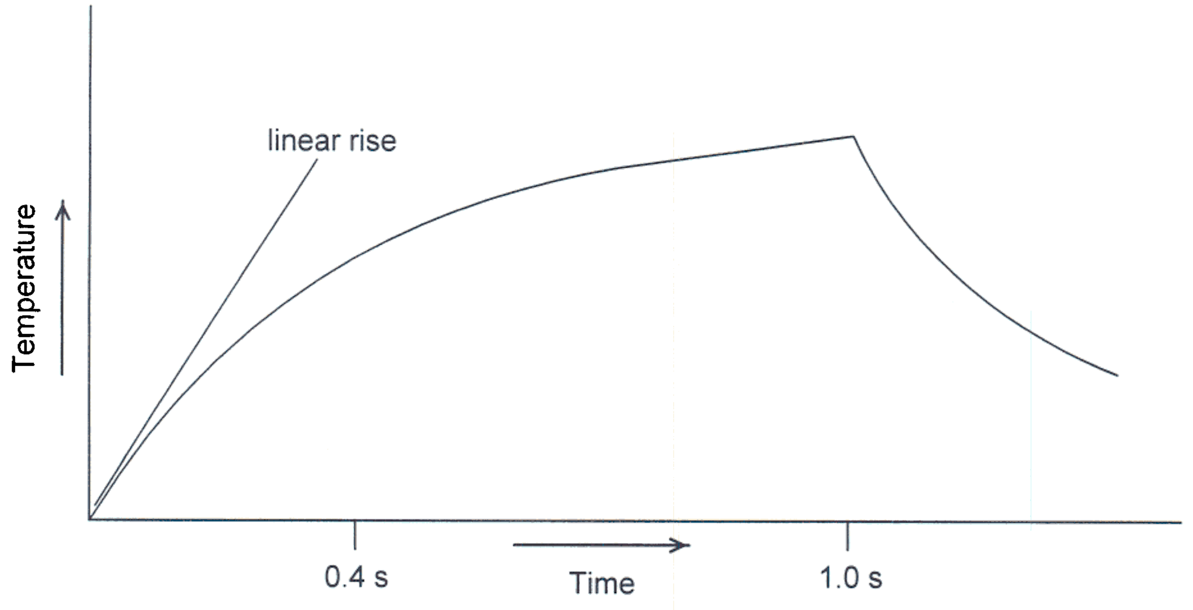

Figure 6: Temporal response of a typical thermal probe

As the temperature of the sensor rises, heat losses occur due to conduction, convection and radiation. An equilibrium temperature is reached when the rate of heat loss is equal to the rate of energy absorption. This equilibrium temperature can also be a linear function of the ultrasonic intensity, provided the losses (including enhanced convection losses due to streaming caused by the ultrasonic beam) are proportional to the difference between the temperature of the probe and that of the water bath[51]. The physical construction of probes of this type is normally in the form of a cylindrical block of encapsulating material about the thermal device, or sometimes with the thermal element suspended via its connecting leads on a frame, allowing the acoustic beam to pass through the support in a similar fashion to that employed in hydrophone construction. Figure 7 shows typical discrete thermistor designs.

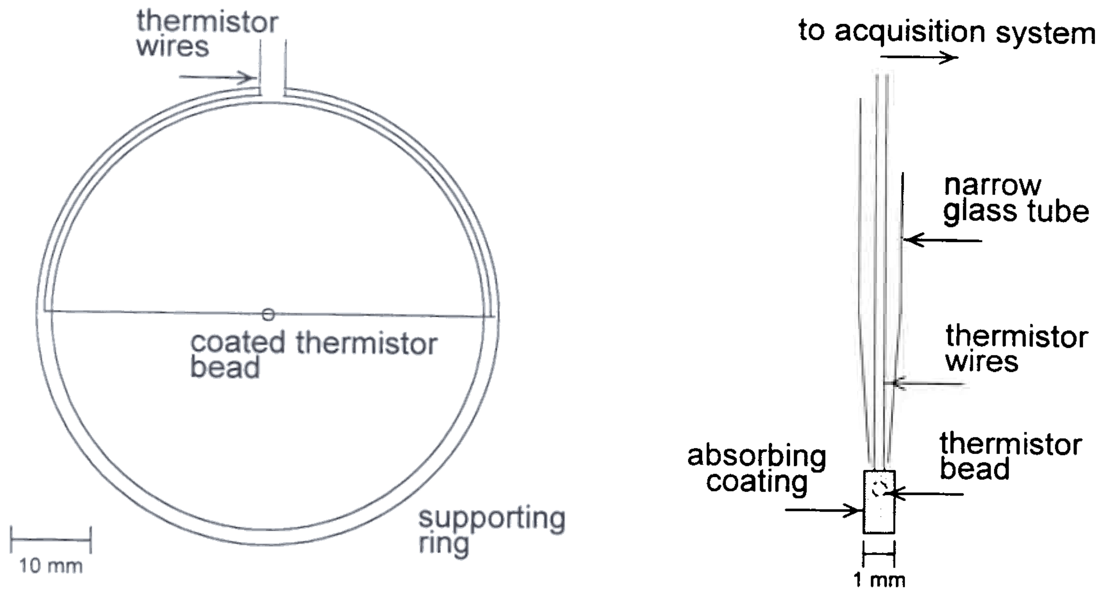

Figure 7: Typical thermistor probe designs

Similar devices can be constructed using thermocouples, with the addition of an amplifier in the signal chain. In characterising a 980 kHz field, Fry and Fry[50] used a design similar to the suspended thermistor case in Figure 7, but with two polyethylene diaphragms stretched over the supporting ring with the void between them filled with castor oil, which provided high absorption in the immediate vicinity of the uncoated thermocouple used. The rise in temperature observed in the presence of ultrasound is thought to result from two phenomena: conversion of the acoustic energy in the field into heat by viscous forces acting between the thermocouple wire (or thermistor casing) and the embedding medium, and absorption of sound in the body of the embedding medium.

Thermal probes can be fabricated with an extremely small measurement volume and are hence well suited for performing measurements of local intensity. In practice, however, there is a trade-off between limiting the dimensions of the sensor and obtaining an observable temperature rise. It should be noted that thermocouple probes measure the *relative* acoustic intensity as a function of temperature: absolute intensity measurement requires prior calibration, or accurate knowledge of the acoustical and thermal properties of the absorbing medium. Studies have been undertaken to evaluate suitable absorbing materials and encapsulation configurations[52].

4.1.1 Application of thermal probes to the characterisation of high power fields

Thermal probes are applicable to measuring high power fields in that their response is omnidirectional, and they can often yield results of fine spatial detail - thermocouple devices may be made as small as 10 μm. However, reproducibility of probe manufacture can be a problem, particularly when using encapsulating materials, as any trapped air in the absorber will alter the acoustic properties of the material. In addition, the acoustic properties of the absorbing material are often frequency and temperature dependent. Ultrasonic fields at megahertz frequencies produce significant temperature rises, even in devices with thin rubber coatings, whereas materials which have sufficiently high attenuation coefficients at tens of kilohertz are less widely documented. Cavitating bubbles can attack the potting compound, altering the volume of the absorbing material around the thermal device, which affects the sensitivity, and perhaps more importantly, produces small motes in the surrounding liquid, which act as nucleation sites for cavitation. In using a thermal sensor, the ambient temperature must be monitored. Further, the response time of thermal sensors is comparatively slow, meaning that the temporal variation in pulsed fields cannot be resolved.

The temporal response of a thermal probe is also limited: in addition to the few hundred milliseconds over which the rate of temperature increase is linear with intensity, the device must be allowed to cool down between measurements over a period of several seconds. In procedural terms, this means switching off the applied signal, which in the case of performing field distribution measurements in an ultrasonic cleaning bath, for example, may have the effect of changing the standing wave patterns produced, as the time taken for the water surface in such a device to settle down after switching on can be considerably greater than the linear response time of a thermal sensor.

Recently, the literature has shown research groups revisiting this measurement technique, in conjunction with computer-controlled positioning and acquisition systems[53,54,55]. This recent work has moved towards the characterisation of fields produced by ultrasonic generators employed in sonochemistry applications, when previously, much of the research in the 1970s and early 1980s was orientated towards medical fields. This shows a growing awareness amongst research groups of the need for spatial information of the intensity distribution. Continued work in this area will enable optimum vessel geometries and insonification configurations to be determined and may ultimately establish a set of measurement techniques that will enable results from different research groups on similar chemical reactions to be intercompared.

The spatial distribution of the acoustic intensity in an ultrasonic field has been assessed using a thermal technique, and the results compared with spatial information on the extent of acoustic cavitation, assessed by foil erosion and chemical dosimetric techniques[10], the Sarvazyan dye method (see below)[56], by a hydrophone[57], and by a chemiluminescent method[58]. The results seen in the latter case are of interest, as the authors discovered that the sites in the acoustic field where the highest number of OH• radicals were produced (illustrated by the level of chemiluminescence observed), which correspond to cavitation "hot-spots", did not correspond to the positions at which the highest output levels were shown by the thermocouple probe output. They suggested that this provides evidence to indicate that a significant part of the ultrasonic energy delivered to a liquid volume is probably not used to induce sonochemical changes. This may also indicate that the presence of the thermocouple probe causes sufficient perturbation such that the regions of highest intensity are displaced from their true locations. However, the authors showed that the intensity distribution measured with the thermocouple probe agreed with conventional plane-piston transducer theory.

4.2 DISCRETE THERMAL METHODS - MULTI-ELEMENT PROBES

In the 1970s the IEC published a report which summarised the position on standardisation for establishing the output of an ultrasonic cleaning bath[59]. Part of the work involved an assessment of a multi-element thermal probe designed and produced in Germany which utilises many of the same principles described above, but which provides spatially-averaged acoustic information, by employing an array of linked thermal sensors[60]. The instrument consists of 32 coated thermocouples, mounted on "stalks" projecting from a central sphere. The outputs from the thermocouples are integrated, and the overall device output takes the form of a DC voltage. The dimensions of the device are such that it corresponds to half a wavelength in water at 20 kHz, which is equal to the separation of successive nodes or antinodes in a standing wave field. In this way, the authors predicted that the device would produce the same output, regardless of its location when positioned in a uniform standing wave field at 20 kHz, generally the most common frequency for cleaning tanks.

Each thermocouple element was coated in a form of Perspex® which had been aerated to increase its acoustic absorption properties. Unfortunately, the apparent variation in probe output with dissolved gas content in the surrounding liquid led to it being rejected as the basis of a standard measurement technique by the IEC. However, a device of this type that produces a spatially-averaged figure for the energy density in a cleaning bath is potentially useful as a routine monitor of cleaning bath output.

4.3 BULK THERMAL METHODS

In applications such as sonochemistry, a more global measure of the "energy" entering a fluid volume is often of use. This can be achieved by making calorimetric measurements, where the acoustic power delivered is assessed simply by measuring the temperature rise observed when a known volume of liquid of known heat capacity is insonificated for a known time. Care must be taken in reducing errors due to heat losses, and contributions to the temperature rise from acoustic source inefficiency. In a controlled environment, useful absolute power data can be obtained[61,62,63,64,65]. Ratoarinoro et al[66] compared different power measurement techniques for both electrical input and acoustical output power with chemical yield for a given reactor, as a function of liquid height in the vessel, and concluded that the dissipated acoustic power density appeared to show the best correlation with reaction yield.

Some sonochemists make an estimate of the acoustic intensity in a vessel by simply dividing the power (derived from calorimetry or electrical power measurements) by the area of the radiating horn tip or bath surface[10]. While acceptable as a very rough means of comparing different sonicating devices, this is by no means an adequate way of quantifying the acoustic field, due to uncertainties in the effective area of the probe tip.

5 RADIATION FORCE METHODS

Targets placed in the path of an acoustic beam experience a unidirectional force, known as the radiation force. Characterisation methods based on the measurement of this force predate the use of piezoelectric hydrophones[67]. Such methods can be used to provide data on both spatially-averaged and local intensities, depending on the size of the target relative to the ultrasonic beam dimensions. The radiation force experienced by the target per unit area is proportional to the ultrasonic intensity in the field. This manifests itself either by a measurable change in the target "weight", in the case of a large target, observed on a balance; or by a linear displacement, seen for a small target and measured with a travelling microscope. A large target which covers the total effective beam area provides the total power, whereas a small target totally immersed in the field will provide local information on the time-averaged intensity.

This would appear to be a simple and inexpensive method, but is very limited in its applicability to typical high power fields. Radiation force devices are used for making power measurements in the megahertz frequency range, but the rapidly-diverging fields produced by high power devices (for example, sonochemical processors) operating in the tens of kilohertz range would be difficult to characterise, unless the beams were collimated in some way. Also, consideration would need to be given to the propagation medium used, as cavitation bubbles will scatter the acoustic field.

The cavitation bubble activity produced by lithotripter fields is generally longer lasting than the acoustic pulse itself, and these events may also cause a measurable force on a target. This effect forms the basis of a measurement device recently reported in the literature[68]. The device consists of an electromagnetic velocity sensor linked via a short rigid rod to a stainless steel ball. This ball is placed underwater at the focus of a lithotripter, and the violent cavitational activity produced by an incident shock wave causes the ball and rod to move. The output voltage from the electromagnetic probe is measured on an oscilloscope, and is proportional to the velocity of the steel ball. The square of the probe output voltage is therefore proportional to the energy transferred to it. Measurements have also shown that there is a linear correlation between lithotripter pulse energy and the amount of synthetic stone destruction. Recent results would seem to reinforce this, and indicate also that the probe responds directly to cavitation activity[69].

6 SEMI-QUANTITATIVE TECHNIQUES

With the exception of thermal probes, the majority of the devices described above represent state-of-the-art measurement techniques, and tend to be expensive. With this in mind, Sarvazyan et al have developed a technique that requires the bare minimum of conventional laboratory supplies and reagents, and in principle, can be calibrated to provide reproducible acoustic data[70]. The technique is based upon the ability of ultrasound to increase the diffusion rate of liquids into porous media. When a piece of white paper is placed in a tank to which a few drops of water-soluble dye (0.1% methylene blue) have been added, and the transducer switched on, the rate of diffusion of dye into the paper is proportional to the local ultrasonic intensity: this was assessed over a wide range of exposure times. The authors correlated the technique with measurements made using a thermocouple probe. In theory, the technique may be calibrated by assessing the optical density of the exposed indicator paper.

The hostile conditions produced by ultrasonic cleaning baths have prompted studies on rugged, semi-quantitative devices for assessing the spatial distribution of the acoustic field. An example[71] is based on the principle of piezoelectricity, but consists of a waveguide attached to a conventional transducer. The device hence comprises an exponential horn with a tip diameter of 1 cm, attached to a PZT crystal. The bandwidth of the system was thought to be in the range 20-40 kHz. The probe is essentially a sonochemical horn, operating in receive mode. Assuming that the horn acted as a perfect waveguide, the authors used the output voltage to derive relative intensity values in making measurements of the spatial distribution of two commercially-available cleaners. The device is not without its merits, as it is simple to use and durable. However, the extent to which it perturbs the field must be of concern.

Ultrasonic cleaning bath manufacturers have also developed semi-quantitative methods for characterising their devices. One example of this is the Ultraprobe[72], developed by Zenith Manufacturing in the US. The device consists of a column of "ultrasonic wave energy responsive fluid medium" in which "ultrasonic wave energy responsive visible particles" are suspended. It works on the principle of particulate movement: when the probe is placed in an ultrasonic cleaning bath, the suspended particles migrate to the standing wave nodes produced, thereby giving a visual indication of the standing wave field distribution in the cleaning bath.

7 SUMMARY

This review has shown that although high power ultrasound has a wide variety of applications, ranging from healthcare to welding, there are comparatively few measurement techniques that have been developed specifically for characterising the acoustic fields produced. Table 1 summarises the techniques described in this report that are applicable to high power field characterisation, with some comparison of their attributes.

Device ⇒ ⇓ Property	Membrane hydrophone	Needle hydrophone	Discrete thermal probe	Multi-element thermal probe	Fibre optic hydrophone	Interferometric methods
Physical effect	piezoelectricity	piezoelectricity	thermal absorption	thermal absorption	dn/dp	membrane or pellicle movement
Parameter	acoustic pressure	acoustic pressure	spta acoustic intensity (relative)	sata acoustic energy density (relative)	acoustic pressure	particle displacement or velocity
Spatial resolution	40 μm	75 μm	10 μm	spatially-averaging	0.1 mm	50 μm
Bandwidth	100MHz	30MHz	Dependent on absorbing material	Dependent on absorbing material	potentially >3GHz	up to 100 MHz
Sensitivity	20 nV Pa^{-1}	40 nV Pa^{-1}	-	0.1 mV /Jm^{-3} (increases as f^2)	4 nV Pa^{-1}	60 nV Pa^{-1}
Pressure range	Up to 100 MPa	Up to 60 MPa	Not proven	Not proven	50 MPa	Potentially large
Comment	Can be damaged by cavitation. Expensive.	Can be damaged High sensitivity. Frequency response unpredictable	Cheap, easy to use. Subject to cavitation erosion damage in high intensity fields, and perhaps shielding and streaming effects	Can be subject to cavitation damage in high intensity fields: Patent refers to device suitable for use in 20 kHz fields only.	Upper frequency limit determined only by λ of light used.	Figures taken from references 44 & 49. High power capabilities not yet fully tested.
References	17-20, 26	8, 13-16, 28, 29	50-58	59,60	34-43	44-49

Table 1: Summary of key measurement techniques for high power ultrasound fields

The majority of the accurate, reliable techniques that have been reported relate to the medical uses of ultrasound, and have been limited in their adaptation to other applications. Most industrial applications (including sonochemistry and cleaning) are currently not subject to the same demand for control of exposure as in medicine, and the characterisation techniques uncovered reflect this. Researchers are using techniques which are simple and inexpensive to apply, but which yield information which is thought to relate to some aspects of the field which are relevant to the process: for example, in assessing the fields produced by sonochemistry processors, a calorimetry technique is used to provide a global indication of the power delivered to the sample. However, more recent literature is showing that information on spatial distributions is becoming essential, and the direction that current studies are taking is starting to reflect this.

From the techniques described in this review, the following were highlighted for evaluation against the criteria of the measurement technique scoring system (see Section 6.1 of main report[1]):

- Piezoelectric hydrophone
- Fibre-optic hydrophone
- Discrete thermal methods
- Electromagnetic probe
- Optical interferometry
- Semi-quantitative techniques

This review has majored on conventional measurement techniques which have been or are being applied to high power cavitating fields. However, it is possible to envisage alternative methods being developed. For example, research on the measurement of acoustic intensity at audio frequencies in air may also have application to waterborne ultrasound. Kuttruff and Schmitz[73] have developed two designs of intensity probe, based on multi-microphone technology in a geometry consisting of a number of sensors located on the surface of an imaginary sphere. The devices measure the intensity vector.

Further developments in polymer technology will also influence sensor designs. Very thin films of PVDF are available, which enable construction of hydrophones with larger bandwidths, and of finer spatial resolution. A sensor that combines both field measurement capability and cavitation monitoring features could be possible, and may find extensive application with appropriate frequency-domain processing.

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