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THE CALIBRATION OF HYDROPHONES FOR USE IN MEDICAL ULTRASONIC FIELDS - A REVIEW

by

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N A T I O N A L   P H Y S I C A L   L A B O R A T O R Y

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SUMMARY

A growing concern for the safety of patients exposed to medical ultrasound has highlighted the importance of the characterisation of medical ultrasound equipment in terms of absolute acoustical parameters. To meet this need, various types of miniature piezoelectric hydrophone have been produced to measure the temporal and spatial distribution of acoustic pressure in the ultrasound field. However, in order to measure absolute acoustic pressure, the receiving sensitivity of the hydrophone must be determined over a range of frequencies. This report reviews the many techniques available for calibrating hydrophones, giving details of the method, the validation and the accuracies achieved. The current state of each technique is described together with the results of comparisons between techniques and between laboratories. An important contribution to the international standardisation of some of the more established techniques has been the publication of certain standards which are also reviewed.

CONTENTS

1. INTRODUCTION

1.1 Rationale

Miniature piezoelectric hydrophones are widely used for the determination of the spatial and temporal distribution of acoustic pressure in ultrasonic fields produced by medical equipment. The use of hydrophones is, in fact, the method recommended for measuring many parameters deemed important by the American Institute of Ultrasound in Medicine and the National Electrical Manufacturers' Association (AIUM/NEMA) [1], by the Food and Drug Administration (FDA) [2, 3] and by the International Electrotechnical Commission (IEC) [4].

There are three main designs of miniature piezoelectric hydrophone: firstly ceramic needle probes [5] consisting of a small piezoelectrically-sensitive ceramic (eg PZT) element mounted on the end of a needle-type probe; secondly polyvinylidene fluoride (PVDF) needle probes [6] which have a PVDF element, and thirdly PVDF membrane hydrophones [7, 8] which consist of a thin film of PVDF stretched over a rigid annular ring, only a small diameter element in the centre being piezoelectrically sensitive. These three types are illustrated in Figure 1.

A knowledge of the receiver sensitivity of the hydrophone as a function of frequency is necessary to make accurate measurements and to ascertain the levels of uncertainty. This requirement has become more apparent following the work of Smith [9] and of Shombert and Harris [10], which demonstrates the errors in the measurement of peak acoustic parameters when a hydrophone with an inadequate frequency response is used.

At present there is no universally accepted standard technique for the calibration of hydrophones in the low-megahertz frequency range. There are, however, several methods which have been used in the past and some new methods which are being developed.

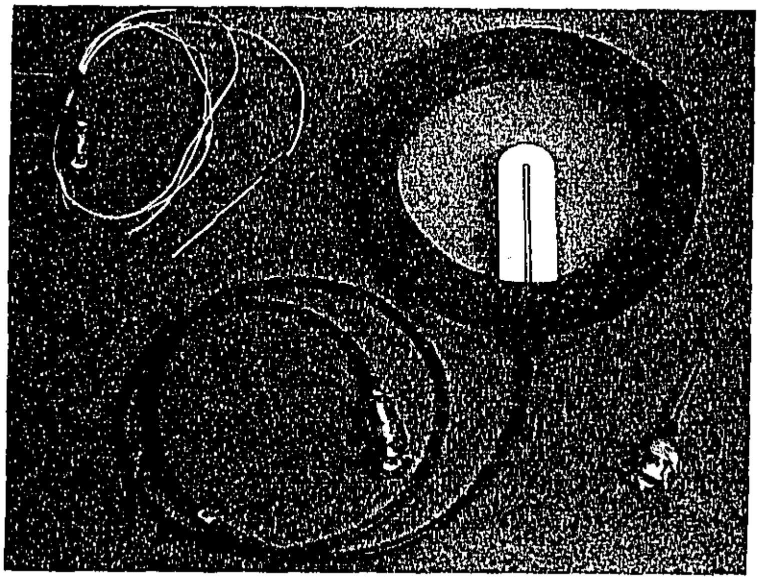

Figure 1 Three main types of hydrophone. From left to right: PVDF needle probe; PVDF membrane and ceramic needle probe.

The techniques will be split into two main categories for this review: firstly absolute techniques and secondly comparison techniques which rely on a previous calibration of a standard hydrophone using an absolute technique.

In this review the relative merits and state-of-the-art of each technique are considered, bearing in mind the following criteria:

Accuracy and precision
Time taken for calibration
Frequency range covered
Number of frequency points within range
Relevance of technique to all hydrophone types.

1.2 Absolute calibration techniques

The absolute calibration of a hydrophone is usually accomplished by measuring the output voltage from the hydrophone when placed in an acoustic field at a point where the absolute value of one of the parameters of that field (such as the acoustic pressure amplitude) has been previously determined using a method which is traceable to fundamental electrical or mechanical units.

Many techniques have been described in the literature for the absolute determination of acoustic field parameters. Some of these, such as calorimetry and total radiation force measurement by means of a sensitive balance, involve the determination of physical quantities averaged over time and over all or most of the acoustic beam. Others, such as optical interferometry or the use of a small thermocouple placed in the field, yield values of spatially-resolved physical quantities. All of these examples determine field parameters by measuring the effect of the ultrasonic field on some sensing device other than an electroacoustic transducer. However, one method, the reciprocity technique, involves measuring the effect of the field on a second transducer or even the effect back on the transducer which is generating the field.

There are then, various different techniques for measuring acoustic field parameters which, if implemented correctly, should give equivalent results. There is an increasing body of evidence in the literature and in the work of standards laboratories suggesting that the results obtained with different methods are indeed in agreement.

There is a review of techniques for measuring ultrasonic field parameters by Haran [11] which also includes the visualisation of ultrasonic wavefronts. Some of these techniques are qualitative and do not fall within the scope of this review as they are not relevant to hydrophone calibration. A review by Stewart [12] deals with techniques for measuring total output power and the spatial distribution of ultrasonic fields; these are more relevant to hydrophone calibration. Neither Stewart nor Haran deals with the application of the measurement techniques to hydrophone calibration, which is the aim of the current review. However, all of the techniques mentioned in these reviews which are applicable to hydrophone calibration are covered.

1.3 Calibration by comparison with a standard hydrophone

The purpose of relative methods of calibration is to provide a rapid determination of sensitivity over a wide frequency range by measuring the output from several hydrophones (including a standard hydrophone) placed at the same point in an acoustic field. Several authors have described improvements to this basic method which either increase the speed of the measurements by calibrating at several frequencies at the same time or increase the number of frequency points at which calibrations can be made.

The overall calibration uncertainties, if these methods are used, are always larger than for absolute techniques because the uncertainty in the absolute calibration of the standard hydrophone itself has to be combined with that from the comparison. This disadvantage may be offset by the increased speed of obtaining results.

1.4 The expression of hydrophone sensitivity

There has been some disagreement in the literature over the most appropriate definition for the sensitivity of a hydrophone. Certain authors recommend the use of an intensity response factor which can be defined as the ratio of the square of the output voltage from the hydrophone to the instantaneous acoustic intensity at the active element [13]. However, as a hydrophone actually responds to acoustic pressure (because the piezoelectric effect results in a pressure-induced charge), the intensity response factor relies on the assumption that the instantaneous intensity is proportional to the square of the acoustic pressure. This approximation is only valid when the acoustic pressure and particle velocity are in phase, such as for plane or spherical waves. Thus, the use of the intensity response factor is not valid in fields which do not satisfy this criterion (eg near a transducer face [14]). For this reason, the pressure sensitivity M will be used in this review, defined as $M = U/p$ where U is the output voltage and p is the instantaneous free-field acoustic pressure in a plane-wave acoustic field at the element of the hydrophone.

There have also been discussions about whether the voltage U should be an open-circuit voltage or a voltage measured with a specified electrical load connected. Chivers and Lewin [15] recommend the use of the latter, giving an end-of-cable sensitivity, as this is the measured parameter and therefore there is no requirement to correct for the load impedance. However, for the calibration to be applicable under different load conditions it is advantageous to specify an end-of-cable open-circuit sensitivity together with the relevant formula for determining the sensitivity when connected to a load of known impedance. This is the policy adopted at the National Physical Laboratory (NPL) and by the IEC [4]. The conversion is given by the following equation:

$$M_L = M_c \left\{ \frac{Re(Z_L)^2 + Im(Z_L)^2}{[Re(Z_L) + Re(Z)]^2 + [Im(Z_L) + Im(Z)]^2} \right\}^{1/2} \qquad (1)$$

where M_L is the end-of-cable sensitivity into a load of complex impedance $Z_L = Re(Z_L) + iIm(Z_L)$, M_c is the end-of-cable open-circuit sensitivity and $Z = Re(Z) + iIm(Z)$ is the complex output impedance of the hydrophone. This expression can be derived from the work of Beissner [16]. If the load can be approximated by a parallel combination of capacitance C_L and resistance R_L then the complex impedance can be calculated using:

$$Re(Z_L) = \frac{R_L}{1 + \omega^2 C_L^2 R_L{}^2} \qquad (2)$$

and

$$Im(Z_L) = \frac{-\omega C_L R_L^2}{1 + \omega^2 C_L^2 R_L^2} \qquad (3)$$

where ω is the angular frequency. A further simplification is possible if the impedances of both the hydrophone and the load can be assumed to be capacitative. In this case, if C is the end-of-cable capacitance of the hydrophone, including any integral cable and connector, equation (1) reduces to

$$M_L = M_c \left(\frac{C}{C + C_L} \right) \qquad (4)$$

As the pressure sensitivity will be used throughout this review, all uncertainties in sensitivities will be expressed as a proportion of pressure or voltage and not in terms of intensity, as given in some of the papers reviewed. Hydrophone sensitivities are sometimes quoted in the literature in dB re 1 V/μPa, but this is inconvenient as ultrasonic hydrophones typically have sensitivities as low as -260 dB re 1 V/μPa. In this review sensitivities will, therefore, be stated in terms of μV/Pa.

2. ABSOLUTE CALIBRATION

2.1 Reciprocity

The existence of reciprocity theorems for mechanical, elastic, acoustical and electromagnetic systems has been known for a long time and these theorems have been discussed by various authors [17]-[19]. The first derivation of the reciprocity relationship between the action of a linear, passive, reversible electroacoustic transducer as a receiver and as a transmitter was by Schottkey [20]. The relationship is based on the theorem that the receiving and transmitting responses of such a transducer are related by a parameter which is independent of the geometry or construction of the transducer. This parameter can be computed from the following relationship:

$$\frac{M}{S} = J \tag{5}$$

where:

J = reciprocity parameter
M = receiving voltage response
S = transmitting current response.

This result can lead to the absolute calibration of a receiver which does not itself have to be reversible [21].

2.1.1 Three-transducer reciprocity

The theoretical basis for this type of measurement was outlined by MacLean [22] in 1940, who obtained a calibration in terms of the open-circuit voltage or short-circuit current. If the transducer is in free space and it does not significantly perturb the acoustic field, a free-field calibration is obtained, and if the transducer is in a chamber a pressure calibration is obtained. The free-field calibration is the one which is relevant to ultrasonic hydrophones. To obtain this calibration it is necessary to calculate a value for the reciprocity parameter and MacLean derived the following relationship for spherical waves:

$$J = \frac{2D\lambda}{\rho c} \qquad (6)$$

where:

D = the distance from the transducer to which the transmitting response is referred

λ = wavelength of the sound

ρc = the characteristic impedance of the medium.

MacLean considered experiments using three transducers: the receiver being calibrated X , a reversible transducer Y and a transmitter Z. The first two measurements are made in the sound field of Z at a distance D along the axis where $D \gg \ell$, the largest dimension of X, Y or Z. The open-circuit voltage U generated by X at this position, and the voltage U_1 generated by Y at the same position, are measured. Since the sound field is the same in both cases, then by definition:

$$\frac{U}{M} = \frac{U_1}{M_1} \qquad (7)$$

The third measurement is of the open-circuit voltage U' generated by X at a distance D along the axis of Y which is driven by a current I'. The free-field pressure at the centre of X is $I'S_1$, where S_1 is the transmitter current response of Y at a distance D along its axis. It follows that:

$$U' = MI'S_1 \qquad (8)$$

and substituting equations (5), (6) and (7) we have:

$$M = \left(\frac{U}{U_1} \quad \frac{U'}{I'} \quad \frac{2D\lambda}{\rho c}\right)^{1/2} \qquad (9)$$

Equation (9) is the absolute free-field calibration of the receiving transducer. This method is attractive since it permits the determination of acoustical quantities from electrical and length measurements without reference to a primary acoustical standard.

According to Foldy and Primakoff [23] the proof of the reciprocity theorem (equation (6)), as given by Schottkey and MacLean, could not be assumed to be universal since it was based on an assumption which they claimed had not only never been proved but is not generally valid. McMillan [24] seems to have been the first to show that the reciprocity theorem itself is not always valid and that it is possible to construct transducers which do not obey the theorem. Foldy and Primakoff presented a full theoretical proof of the reciprocity theorem for electroacoustic transducers which provides conditions necessary for its validity. These conditions are: (i) the existence of certain symmetry relationships among the transducer parameters; (ii) that the coupling is either purely electrostatic or piezoelectric or both, or purely electromagnetic or magnetostrictive or both; (iii) that the transducer does not radiate electromagnetic waves from its surface. Piezoelectric transducers in general conform to these conditions and to those specified by MacLean.

Foldy and Primakoff also made certain observations regarding the execution of a reciprocity calibration as described by MacLean. These observations concerned the choice of electrical terminals on the reversible transducer and on the receiving transducer being calibrated, and also the correction for the use of a finite load impedance instead of an open-circuit. They also applied more stringent criteria for D, the distance between transducers, because Maclean was dealing with audio acoustics where the former criterion was, in general, more restrictive. The new criteria were:

$$D \gg \ell, \quad D \gg \ell^2/\lambda \tag{10}$$

where ℓ is the largest dimension of any of the three transducers used. They stated that if these criteria are met then the calibration is effectively that for plane waves, because at distances greater than ℓ^2/λ (known as the far field) the acoustic field locally approximates to a plane wave.

In 1949, Simmons and Urick [25] developed a plane-wave reciprocity parameter J_p for use when all the transducers are plane piston radiators and where the transmitter-to-receiver distance D is very short so that the hydrophone is in the near field of the transmitting transducer. Figure 2 shows the extent of the plane-wave region with experimental results obtained for an identical transmitter and receiver. (For a normalised distance of less than 2 these appear to contradict the theoretical curve in Figure 5 which represents a hydrophone/transducer diameter ratio of unity.)

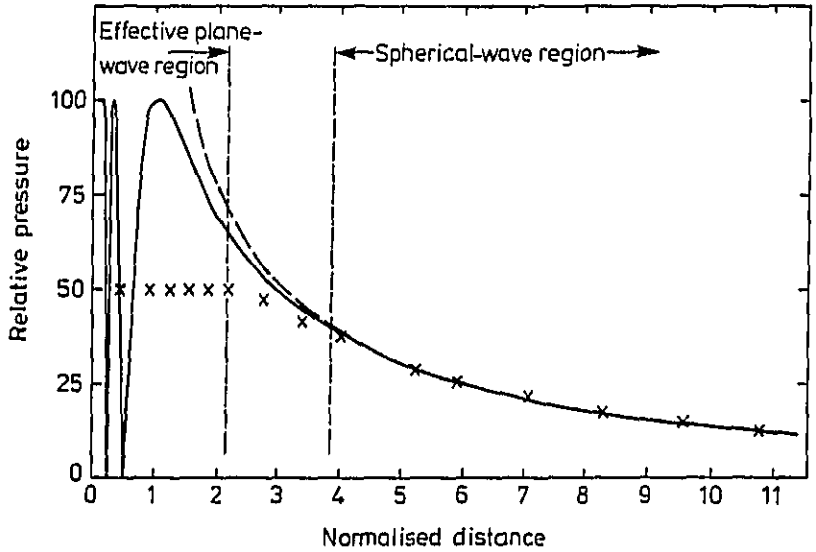

Figure 2 Sound field of a circular piston radiator as measured by Simmons and Urick [25]. The solid curve is the pressure on the axis; the dashed line is the pressure of an equivalent point source and the crosses are measured pressure averaged over the transducer area using pulse-echo. Normalised distance is D/N where N is the distance a^2/λ and a is the radius of the transducer.

In 1961, Bobber and Sabin [26] derived a cylindrical wave reciprocity parameter J_c for transducers which are effectively line sources placed parallel to each other. They also pointed out the consistency between the three reciprocity parameters:

Spherical waves	$J_s = [2/(\rho c)](D\lambda)^1$	
Cylindrical waves	$J_c = [2/(\rho c)](D\lambda)^{1/2}L$	(11)
Plane waves	$J_p = [2/(\rho c)](D\lambda)^0 A$	(12)

where L is the length of the line source and A the area of the plane piston source. The $(D\lambda)^0$ in equation (12) is superfluous but illustrates that the power of $D\lambda$ in each expression is the same as the power of D in the spreading of sound pressure for each kind of wave. The effective size of the transducer is finite for cylindrical and plane waves and the finite dimensions appear as L and A.

Trott [27], in 1962, derived the plane-wave and cylindrical-wave reciprocity parameters from the radiated power in the near and far fields of transducers, thus confirming the above findings. Further work by Bobber [28] derived the separate reciprocity parameters from a general reciprocity parameter. He also generated reciprocity parameters for coupler-reciprocity systems, for diffuse sound and for Beatty's-tube reciprocity [29].

Although it is possible to calibrate a miniature ultrasonic hydrophone using three-transducer reciprocity, it is difficult to extend the calibration up to frequencies which can be used in medical ultrasound. This is due to the directionality of these devices at megahertz frequencies, making alignment very difficult. Lewin [6] has calibrated a hydrophone probe in 50 kHz steps up to 6.5 MHz to intercompare the technique with two-transducer reciprocity (see Section 2.1.3) but there have been very few attempts to use it for hydrophone calibration because of the much simpler techniques, described in Sections 2.1.2 and 2.1.3, which use short tonebursts of ultrasound and thus reduce the problem of reflections in the water tank.

2.1.2 Self-reciprocity

By an extension of the reciprocity principle for the absolute measurement of sound, Carstensen [30] demonstrated that a calibration may be obtained on a single transducer without the aid of auxiliary transducers, thus speeding up the calibration procedure. Obviously the transducer must be reversible and must satisfy the conditions described by Foldy and Primakoff [23] for observance of the reciprocity relationship. This technique cannot be used for all ultrasonic hydrophones as many are too small to be used as projectors. However, the self-reciprocity technique is the basis of the two-transducer reciprocity calibration (see Section 2.1.3) which can be used for most hydrophones.

In this method a perfect acoustic reflector is placed a distance D/2 from the transducer which is excited by a short sinusoidal toneburst with current amplitude I_1, generating a corresponding toneburst of acoustic energy. After striking the perfect reflector the ultrasound is received by the transducer producing an open-circuit voltage amplitude U_1.

Using the same definitions as in Section 2.1.1 (equation (8)):

$$U_1 = M_1 S_1 I_1 \tag{13}$$

Substituting equation (6):

$$M_1 = \left(\frac{U_1}{I_1} J\right)^{1/2} \tag{14}$$

Equation (14) gives the receiving sensitivity of the reciprocal transducer in terms of electrical quantities and the reciprocity parameter. Carstensen measured the receiving response of three underwater transducers, comparing self-reciprocity with three-transducer reciprocity, and obtained results up to 0.1 MHz agreeing to within ± 3 dB (± 42%) which was "within experimental error" (see Figure 3).

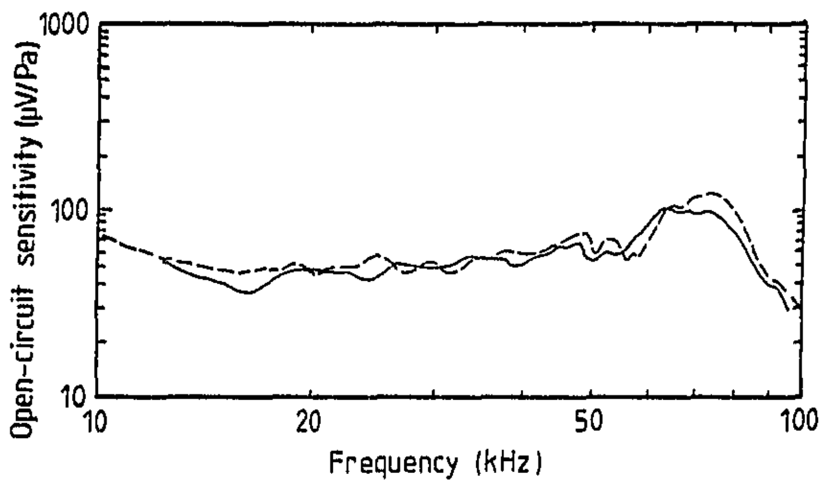

Figure 3 Receiving response of a hydrophone determined by Carstensen [30] using: self-reciprocity (solid line) and three-transducer reciprocity (dashed line).

Although he does not discuss the uncertainties or the sources of error, Carstensen does describe his experimental technique and the problem caused by the amplitude of the transmitting electrical pulse being 100 dB greater than the received pulse. This meant that the receiving system had to be very sensitive and yet unaffected by large amplitude electrical pulses. The difficulty was overcome by the use of diode limiters, but there was still the problem of producing a toneburst short enough to distinguish between the transmitted and received pulses but long enough to define the frequency of calibration and within a tank of limited size. Carstensen, however, performed calibrations up to only 0.1 MHz, whereas at medical ultrasonic frequencies of 0.5 MHz and above this problem is only minor. There are considerable advantages with a toneburst technique, especially in eliminating problems of reflections, standing waves and the effect of electrical pick-up from the transducer.

In 1974, Reid [31] used self-reciprocity to determine transducer efficiency in order to perform dosimetry in medical diagnostic systems. The estimated total uncertainty is stated as ± 30%, arising from several sources. Apparently these could have been reduced by the use of more sophisticated equipment, to give an estimated total uncertainty as low as ± 6%. An important observation made by Reid was that the self-reciprocity technique could be used to establish acoustic fields of known total power and intensity, and that these could be used to calibrate hydrophones that would be too small to be used as projectors. Subsequently, this method formed the basis of the two-transducer reciprocity technique (see Section 2.1.3).

In 1979, Erikson [32] presented a pulse-echo self-reciprocity transducer testing system utilising a 50 ohm transducer termination but he only considered relative measurements of transducer performance rather than absolute measurements. Then, in 1980, Drost and Milanowski [33] suggested that one of the main reasons why self-reciprocity had not been adopted as a measurement standard for ultrasonic transducers was due to the difficulty in obtaining open- and short-circuit measurements in this frequency region. To help overcome this problem, they extended the conventional reciprocity calibration theory to include arbitrarily-terminated transducers. This permitted the use of a standardised (say 50 ohm) termination in the definition of the receiving sensitivity M, and the establishment of a high-frequency transducer specification independent of the driving equipment. In fact, this extension of the reciprocity theory has not increased the use of self-reciprocity for the calibration of small hydrophones as it is not necessary for the technique described in Section 2.1.3.

2.1.3 Two-transducer reciprocity

In 1971, Koppelmann et al [34] reported the use of the self-reciprocity technique (see Section 2.1.2) to determine the acoustic pressure p_1 at the surface of an auxiliary reciprocal transducer for a driving current I_1, after reflection of the wave from a perfect reflector directly back on to the transducer. Using equation (14):

$$p_1 = \frac{U_1}{M_1} = \left(\frac{I_1 U_1}{J}\right)^{1/2} \qquad (15)$$

By placing a probe hydrophone at the point in the field of the transducer where the acoustic pressure at the hydrophone was approximately p_1, it was possible to obtain the free-field pressure sensitivity of the hydrophone by measuring the open-circuit voltage U generated by the hydrophone:

$$M = \frac{U}{p_1} = U\left(\frac{J}{I_1 U_1}\right)^{1/2} \qquad (16)$$

Koppelmann et al performed calibrations in the frèquency range 75 kHz to 2 MHz using this method with the water surface as the perfect reflector and compared the results with those from the three-transducer reciprocity technique up to 250 kHz, obtaining agreement to within ± 2 dB (± 26%).

Brendel and Ludwig [35] have presented a modification of this technique for the megahertz frequency range. Before this time there had been relatively little demand for the calibration of hydrophones for use in medical applications and a number of difficulties in the application of reciprocity had to be overcome. The main difficulties were firstly that in the megahertz frequency range a transducer generally possesses such a complicated directivity pattern that the three-transducer reciprocity technique (see Section 2.1.1) is rendered too troublesome because of the numerous accurate adjustments of the orientation of the transducers required. Secondly, self-reciprocity calibrations (see Section 2.1.2) are often not applicable to the small hydrophones which are required in this frequency range because they cannot be used as projectors.

Unlike Koppelmann et al, who used the spherical-wave reciprocity parameter and calibrated at distances well into the far field, Brendel and Ludwig used conditions that were closer to a plane wave, as described by Simmons and Urick [25] (see equation (12)), and calibrated at a transducer-reflector separation comparable to the near-field length $N = a_1^2/\lambda$ where a_1 is the effective radius of the auxiliary transducer. Figure 2 shows that this distance is within the region where the propagation approximates to that of a plane wave. If a shorter distance were chosen, the measurements with the hydrophone would become extremely difficult due to the complicated structure of the acoustic field. The experimental apparatus is shown in Figure 4.

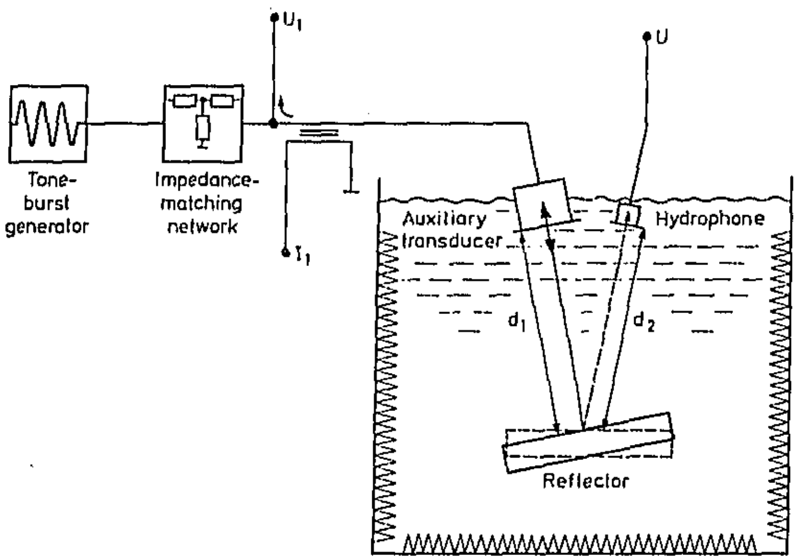

Figure 4 Experimental arrangement for two-transducer reciprocity calibration method used by Brendel and Ludwig [35].

Brendel and Ludwig introduced numerous corrections which become important at megahertz frequencies. The reciprocity parameter must be modified to take into account departures of the field from plane-wave conditions:

$$J = \frac{2A}{\rho c r} \frac{k_{u1}}{k_u^2} \frac{G_1}{G_2^2} e^{2\alpha d_2} \qquad (17)$$

where:

k_{u1} = Correction to open-circuit voltage of auxiliary transducer
k_u = Correction to open-circuit voltage of hydrophone
r = Amplitude reflection coefficient at the reflector
G_1 = Diffraction-loss correction during self-reciprocity
G_2 = Diffraction-loss correction during hydrophone calibration
α = Sound attenuation coefficient of the transmission medium
d_2 = Distance from hydrophone to reflector.

The correction factor k_u is the same as M_c/M_L from equation (1), but Brendel and Ludwig merely state that it can be determined by measurements of the impedances of the hydrophone and the connected load. The factor k_{u1} is defined as the ratio of the short-circuit current I_s to the driving current I_1. The reflection coefficient r is derived from the characteristic acoustic impedances of the materials used and of the transmission medium. Brendel and Ludwig also introduced corrections for reflections at the auxiliary transducer and at the hydrophone. However, the former is incorrect and the latter is inapplicable to free-field calibrations, as acknowledged by Beissner [16].

The factors G_1 and G_2 are functions of the normalised distance $s = D/N$ where D is the total path length from transducer to hydrophone. These corrections are necessary because the hydrophone is not situated in a plane acoustic field. The function G_1 describes the ultrasonic diffraction loss of the auxiliary transducer when self-reciprocity is being performed. The correction G_2 describes the sound pressure averaged over the hydrophone element as a function of the normalised distance and the effective diameter ratio of the transducers. The theoretical curves according to Fay [36] are shown in Figure 5; the values of the G_1 correction are given by the curve for a hydrophone/transducer diameter ratio of unity.

The attenuation coefficient is proportional to the square of the frequency and is temperature dependent. The attenuation only needs to be considered for the distance d_2 between the hydrophone and the reflector because the terms for the other propagation distances cancel.

Brendel and Ludwig measured the free-field pressure sensitivity of

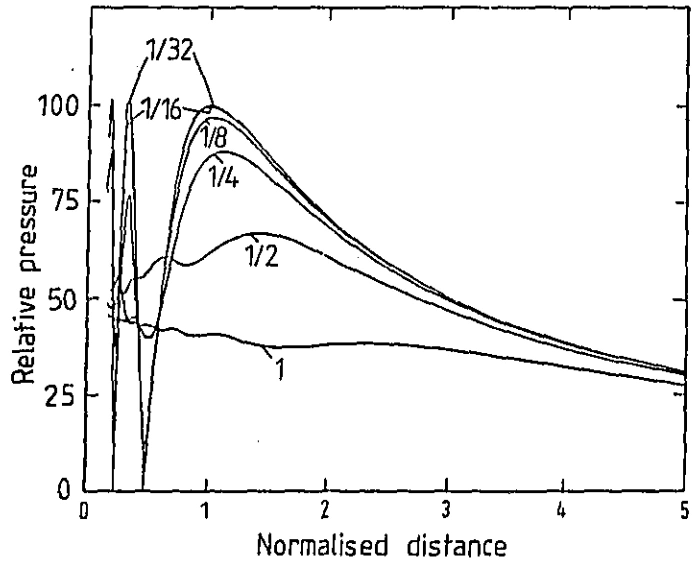

Figure 5 Average pressure versus normalised distance for different hydrophone/transducer diameter ratios.

a probe hydrophone as a function of frequency from 1 to 10 MHz when connected to a specified electrical load (ie the end-of-cable sensitivity). At some frequencies several measurements were made using different auxiliary transducers, requiring the use of different corrections. The variation in these calibration values was generally less than $\pm$ 0.3 dB ($\pm$ 4%). Larger differences occurred above 8 MHz if the nominal transducer diameter was used for the corrections instead of the effective diameter determined from measurements of its field characteristics. Below 1.6 MHz the variation was $\pm$ 1 dB ($\pm$ 12%). A measurement uncertainty of $\pm$ 1 dB in the pressure sensitivity is suggested as the result of an uncertainty of $\pm$ 10% in the near-field length for $0.5 < s < 3$. No estimate is given of the systematic or random uncertainties in the technique but the authors claimed this to be one of the best ways for the precision calibration of small hydrophones at megahertz frequencies.

Beissner [16] presented a theoretical justification for an IEC standard [37] based on the reciprocity technique (see Section 2.1.4). He developed the work by Brendel and Ludwig to include more detailed explanations of the corrections for attenuation and finite electrical loading (from which equation (1) is derived).

Lewin [6] performed two-transducer reciprocity at 20 kHz frequency intervals up to 10 MHz on a PVDF needle probe hydrophone and compared these results with those of three-transducer reciprocity which was performed in 50 kHz steps up to 6.5 MHz. Differences between these calibrations were less than ± 0.5 dB (± 6%) but no uncertainty value is stated. A third calibration was performed but there is no mention of the technique used. These results were used by Gloersen et al [38] in a comparison between reciprocity and planar scanning (see Section 2.2.3) where agreement was within ± 0.5 dB (± 6%) with an uncertainty of approximately ± 1 dB (± 12%) being attributed to each of the measurement methods.

Livett et al [39] and Preston and Livett [40] have described the technique used for reciprocity at NPL which was similar to that of Brendel and Ludwig [35] and to the experimental method recommended by the IEC [37]. The main experimental modification to the technique resulted from the size of the PVDF membrane hydrophones used at NPL [7, 8] which prevented the element of the hydrophone being placed physically close to the auxiliary transducer. For this reason, after calibrating the auxiliary transducer by self-reciprocity, the reflector was removed from the water altogether and the hydrophone placed at twice the distance of the reflector from the transducer. This required an extra factor r^2 (r is the amplitude reflection coefficient at the steel/water interface) in the reciprocity parameter (equation (17)). The systematic uncertainties quoted in the technique used at NPL were estimated by linear summation of the contributing components to be ± 8% at 0.5 MHz, ± 12% at 10 MHz and ± 20% at 15 MHz. Overall uncertainties at the 95% confidence level were: ± 4% at 0.5 MHz, ± 8% at 10 MHz and ± 12% at 15 MHz. The random uncertainty was typically ± 2%. Livett et al [39] and Preston et al [41] analysed the sources of uncertainty in detail, giving the corrections and uncertainties for the finite load impedances used. At NPL, several absolute calibration techniques are used and an intercomparison between these techniques (discussed in Section 4) showed agreement within the estimated uncertainties.

2.1.4 IEC publication 866 [37]

No review of hydrophone calibration techniques would be complete without stressing the importance of international standards which recommend procedures, calculations and corrections, which have been agreed by world experts in the field. Thus IEC standard 866 [37], prepared by Technical Committee 29D, provides just such a consensus of ideas for the two-transducer reciprocity technique. Discussions of the determination of correction factors, the calculation of results and the statement of accuracy are included, as well as details of the recommended measurement conditions and experimental method. The standard recommends use of the plane-wave reciprocity parameter with corrections for diffraction losses as suggested by Brendel and Ludwig [35] and defines a procedure to be used for determining the effective radius of the auxiliary transducer.

2.2 Planar scanning

As an absolute calibration technique, planar scanning relates the value of total time-averaged output power from a transducer (measured using a method which is traceable to electrical or mechanical units) to the integral of the square of the voltage measured by scanning a hydrophone over the whole beam in a plane perpendicular to the beam axis. A value for the pressure sensitivity of the hydrophone can be obtained if the hydrophone is scanned over the beam at a distance from the transducer where the plane-wave approximation of intensity applies [14].

2.2.1 Methods of total output power measurement at NBS

Many authors of papers discussing the planar scanning technique used transducers with a known and reproducible output power such as the calibrated standard transducers provided by the National Bureau of Standards (NBS), Washington, DC. Thus it is relevant to consider the methods used at NBS to measure the total output power from their standard quartz transducers as reported by Millar and Eitzen [42]. Three methods are described for determining the total power or the radiation conductance $G_r = W/V^2$, where W is the power produced by a given input rms voltage V.

The first is an equivalent circuit method [43] for which the NBS standard quartz transducers are very suitable. The equivalent circuit is approximately valid for quartz crystals but not for PZT and other materials. This method requires the measurement of the input impedance of the transducer under three conditions: (i) unloaded (ie with the transducer in air), (ii) loaded (ie with the transducer in water) and (iii) clamped (ie with both faces of the piezoelectric crystal held stationary). To make these measurements, NBS used a special twin-T bridge which is difficult and expensive to obtain. Absolute power levels from 5 µW to about 1 W can be determined by this technique with uncertainties estimated to be less than ± 5%.

The second is a calorimetric method which compares the rise in temperature of an attenuating liquid, due to absorption of the ultrasound, with the temperature rise produced by electrical heating. NBS use a calorimeter developed by Zapf et al [44] which has two cells with absorbing fluid passing through each in identical circuits. While the ultrasound beam heats one cell, an electrical heating element heats the other cell at the same rate, under feedback control, and the electrical power required is measured. This equipment is capable of measuring ultrasonic power from 0.5 mW to 10 W over a frequency range of 1 to 15 MHz. The uncertainty figure quoted is ± (7% + 0.2 mW). A full account of the sources of uncertainty involved and how they were evaluated and combined is given by Zapf et al in another publication [45].

The third method is a modulated radiation force technique which measures the total forward-radiated ultrasonic power. In this method continuous-wave ultrasound is amplitude modulated at a frequency of 39 Hz and the ultrasound is directed vertically upwards towards a conical reflecting target with a half-angle of 45°. The modulated radiation force is measured using an electromagnetic sensor which detects any slight movement of the target and, via a feedback device, applies a restoring force using an electromagnetic drive unit (see Figure 6), thus leaving the target approximately stationary. The technique is claimed to be applicable over a frequency range from 100 kHz to 30 MHz with a total estimated uncertainty ranging from ± 2.2% at 1 MHz to ± 12% at 30 MHz for powers between 10 µW and 10 W. Acoustic streaming is likely to be significant in this system, particularly for frequencies above 10 MHz, although its effect or any preventative measures are not mentioned. However, a re-assessment has since produced larger uncertainties due to streaming effects which are so hard to evaluate that only a maximum possible uncertainty can be estimated by using the total attenuation in the medium.

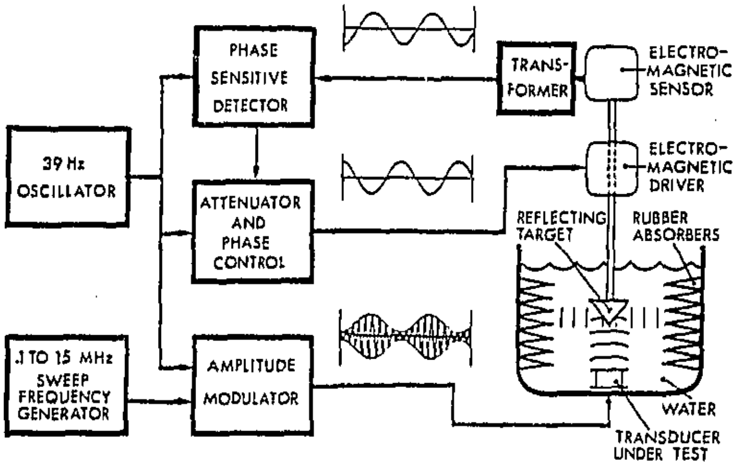

Figure 6 Schematic of the modulated radiation force balance.

A paper by Greenspan et al [46] reports an intercomparison between the modulated radiation force technique and the other two techniques used at NBS. Results are given for 14 different transducers of the air-backed quartz type over the frequency range 2 to 15 MHz. The equivalent circuit method gave agreement with the radiation force technique within the measurement uncertainties for 11 out of the 14 cases. For one of the 5 MHz transducers the error bars failed to overlap by 1.3% whilst for the two 15 MHz transducers the corresponding figures were 4.5% and 9.5%. The calorimetric technique gave systematically lower values than the radiation force technique, but the agreement was within the $\pm$ 7% uncertainty assigned to the calorimeter measurements and in most cases the agreement was much better.

An earlier intercomparison of total power measurement techniques, reported by Stewart [12], involved the equivalent circuit method at

NBS and a radiation force balance, an acousto-optic technique and a calorimetric method at BRH (Bureau of Radiological Health, now Centre for Devices and Radiological Health, CDRH). Two quartz air-backed transducers were used, each with a resonant frequency of 2 MHz. Apart from two of the five measurements using the radiation force method, the results were within ± 8% of the mean value at each power level. However, Haran et al [47] have reported a more recent intercomparison of the acousto-optic and radiation force methods at BRH, using lead zirconate titanate (PZT) transducer crystals, which showed much smaller random uncertainties (± 1.2% and ± 6.3% respectively, at the 95% confidence level) than for the intercomparison conducted by NBS and BRH.

2.2.2 An international intercomparison of total power measurement

After testing their standard quartz transducers, NBS found them to be linear (ie the power output was proportional to the square of the voltage), so that each transducer could be characterised by a single radiation conductance (G_r). They also found that this value was the same, within experimental error, as that determined at low power levels by the equivalent circuit method, and over the range 50 to 750 mW by the calorimetric method. An international intercomparison of measurements of the continuous-wave power emitted by these transducers was arranged [48]; NBS Washington served as the pilot laboratory and there were seven other participating laboratories as follows:

National Bureau of Standards, Boulder, Colorado, USA
Radiation Protection Bureau, Ottawa, Ontario, Canada
National Research Council, Ottawa, Ontario, Canada
Bureau of Radiological Health (now Centre for Devices and Radiological Health), Rockville, Maryland, USA
Ultrasonics Institute, Sydney, Australia
Physikalisch-Technische Bundesanstalt, Braunschweig, FRG
National Physical Laboratory, Teddington, Middlesex, UK.

A total of eight different techniques were used, some laboratories using more than one. They included reciprocity and an optical (Raman-Nath) technique as well as the methods mentioned in Section 2.2.1. Transducers of 2 and 5 MHz resonant frequency were used, with the agreement between the laboratories being best at

5 MHz. However, for the power range 2.5 mW to 2.5 W in all cases except one, the deviation of the average value for each laboratory's technique from the grand average of all the laboratories was less than that laboratory's estimate of the uncertainty.

This international intercomparison represented a large step forward in the establishment of world standards in medical ultrasound by demonstrating agreement between different techniques and between different laboratories.

2.2.3 Calibrations of hydrophones

In 1973, Herman et al [49] calibrated a ceramic needle probe hydrophone at one frequency (1 MHz) using the planar scanning technique and obtained agreement with the sphere radiometer technique (see Section 2.5.2). The only uncertainty quoted is ± 5% in the determination of total power using the radiation pressure on a float. In an attempt by Fischella and Carson [50] to identify and quantify some of the inaccuracies in the use of miniature hydrophones for characterising medical ultrasound equipment, they measured the total power from a focused pulse-echo transducer, firstly using a radiation force balance incorporating a feedback microbalance, and secondly by scanning the acoustic field in the focal plane with a hydrophone calibrated by the manufacturer (Mediscan Inc who used a sphere radiometer, see Section 2.5). Scans in two perpendicular directions were used, assuming cylindrical symmetry. The uncertainty in the measurement of total power was estimated to be ± 25% for both techniques, but discrepancies of approximately ± 300% were found. These large errors were attributed primarily to severe variations in the frequency response characteristics of the ceramic (PZT) material used in the hydrophone, and to the inability to adequately determine that response.

A more promising version of this technique using a PVDF needle probe hydrophone was reported in 1981 by Jones et al [51]. The object of this investigation was to determine the frequency response of the hydrophone over a range of frequencies from 1 to 10 MHz so that the hydrophone could be used to derive acoustic intensities with a small uncertainty; preferably less than ± 30%

(ie with an uncertainty in the pressure sensitivity of less than ± 15%). Again two perpendicular beam plots in either the focal plane or the far field were used, and cylindrical symmetry was assumed. Medical pulse-echo transducers were used as sources and these had been previously calibrated by the NBS (see Section 2.2.1 and [42]). Initially, these transducers were used to calibrate a radiation force balance which had an absorbing target [52]. Calibrations of the hydrophone were then performed at nine frequencies to obtain values for the intensity response factor (see discussion in Section 1.4). To check the calibration, the hydrophone was then calibrated at the Bureau of Radiological Health (BRH) using a similar method which is described below. Figure 7 illustrates the good agreement between the two different methods.

A detailed analysis of uncertainties is presented by Jones et al, including contributions from the following: the assumption of cylindrical symmetry; the reproducibility of the spatial integral; the temporal stability of the hydrophone voltage response; the measurement of voltages; the hydrophone misalignment, and the uncertainty in the independent measurement of total output power by NBS. These uncertainties were combined in quadrature giving a total uncertainty in the pressure sensitivity of ± 12%. The uncertainties in the BRH values are also quoted as ± 12%.

The planar scanning technique used at BRH has been described in several papers [38, 51, 53, 54] but the most complete treatment was produced in 1982 by Herman and Harris [13]. Unfortunately, in this paper the intensity response factor was used and then values for the pressure sensitivity derived assuming the plane-wave approximation. The main difference between the method used at BRH and those already described was the use of a raster scan over a square section of a plane in the far field, a method which did not require the assumption of cylindrical symmetry. It was not possible to integrate over the whole transducer beam because the signal fell below the noise level of the system at a certain distance from the beam axis. At BRH, contributions were excluded beyond a pressure level equal to 10% of the spatial peak value, although AIUM/NEMA [1] recommends a threshold of 5%.

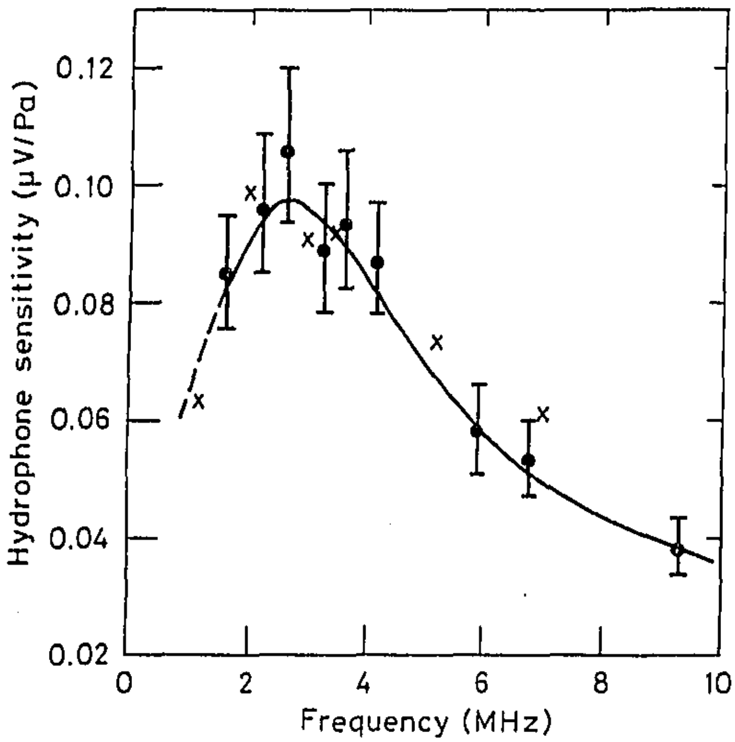

Figure 7 Hydrophone pressure sensitivity as determined by:

- ● Jones et al and
- × BRH.

The curve represents the antilogarithm of a least-squares polynomial fitted to the logarithm of the nine points reported by Jones et al. The values have been converted from the intensity response factors given in [51] assuming the plane-wave approximation of intensity [14] applies.

Herman and Harris discuss several sources of uncertainty hitherto unmentioned: a correction for the attenuation of ultrasound in water; the uncertainty in the rectangular spatial integration across the field; an error due to the spatial averaging of pressure over the finite area of the hydrophone and due to the directivity function of the hydrophone; the contributions missed by using a 10% threshold; a very small uncertainty due to scanning over a plane rather than the spherical surface assumed in deriving the above uncertainties, and finally an uncertainty due to the assumption of the plane-wave approximation of intensity (see [14]). The total measurement uncertainties has been obtained for intercomparisons between planar scanning, reciprocity and interferometry at NPL [41] (see Section 4.1).

2.2.4 The draft IEC standard on planar scanning [56]

As in Section 2.1.4, it is of great importance to discuss the progress in international standardisation of calibration techniques using the planar scanning principle. This type of calibration is recommended by the AIUM/NEMA Safety Standard [1] with some description of measurement procedures. An important contribution to the standardisation of planar scanning is the draft IEC standard [56] being prepared by Working Group 8 of IEC Technical Committee 29D. This document gives definitions of parameters, derivations of equations and a description of the measurement procedure recommended to produce the most accurate results. There is also a comprehensive section dealing with corrections and sources of uncertainty.

This draft standard suggests allowing for the directional response of the hydrophone either by rotating the hydrophone for maximum signal at each point of the scan, or by calculation for frequencies below 5 MHz where the effect of the hydrophone's directivity is less important. Equations are also given for the evaluation of the integral for both diametrical beam scans and a raster-scan technique. Another correction, which has not been mentioned previously, concerns the high-frequency components introduced by finite-amplitude distortion of the waveform due to nonlinear propagation. A criterion is given for the degree of distortion allowable before a specified percentage error is introduced.

This draft IEC standard uses the pressure sensitivity of the hydrophone M_L in all the equations, so corrections and uncertainties are given in terms of pressure rather than intensity. The equation used for determining the hydrophone sensitivity is equation (18) and the recommended correction to open-circuit sensitivity is equation (1).

2.3 Optical techniques

A review paper by Haran [11] on the visualisation and measurement of ultrasonic wavefronts deals extensively with optical methods and divides them into the two main categories of optical diffraction and optical interferometry.

Optical diffraction techniques are largely qualitative and are used for visualising ultrasound beams, although Stanic [57] proposed a schlieren method yielding quantitative measurements of the acoustic pressure integrated along the optical axis. Erikson [58] also used an optical diffraction technique to calibrate a miniature ultrasonic hydrophone. The light beam passed through the ultrasound field of a projecting transducer at the point where a needle probe hydrophone had been placed (see Figure 9). Long tonebursts were required and the ultrasound beam had to be mapped in advance by scanning the hydrophone along the optical axis. This information could be used to calculate the acoustic pressure at a point in the beam on the optical axis from the measured integral of the acoustic pressure along the whole axis. Erikson calibrated hydrophones in this way and claimed sufficient accuracy for use in medical ultrasound characterisation but, if the hydrophone is to be used as a reference standard, he recommends the use of other calibration methods as well. A comprehensive treatment is given of possible sources of uncertainty including: the validity of simple phase-grating (Raman-Nath) theory; the accuracy of the accepted value for the acousto-optic coefficient of water; the effect of the acoustic pulse length compared with the optical slit width; the angle of incidence of light on the sound beam; the homogeneity of the sound field and finite-amplitude effects in water. Reibold [59] has described the measurement of time-averaged acoustic intensity by the evaluation of the surface relief produced by the radiation pressure of a propagating sound wave striking the free liquid surface from the liquid side. The technique used double-exposure holography to reconstruct the surface as a fringe pattern corresponding to the contours of the surface. Surface tension had to be corrected for and an uncertainty of $\pm$ 5% in the measurement of acoustic intensity was estimated.

Optical interferometric techniques are widely used to determine the change in the optical path length of a light beam (usually that

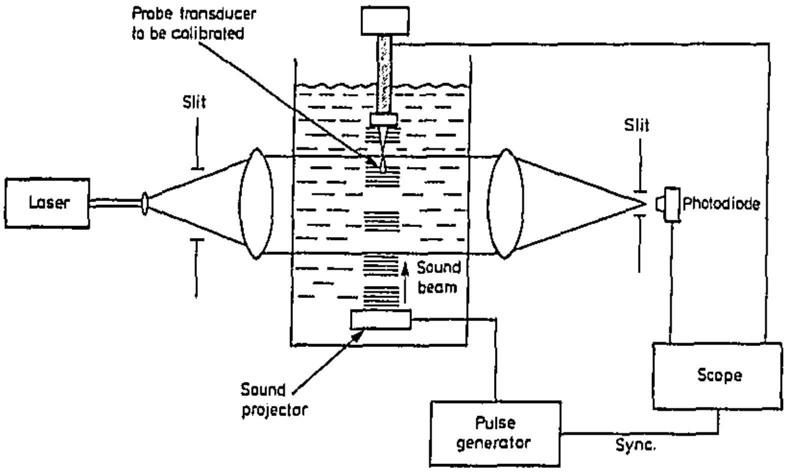

Figure 9 Calibration of a probe hydrophone using ultrasonic light diffraction (after Erikson [58]).

produced by a stabilised laser) and such a method can be used to determine the amplitude of the particle displacement in the acoustic field from a transducer. From this measurement the acoustic pressure amplitude can be derived if spherical- or plane-wave propagation is assumed so that the relationship

$$p = \rho c \omega a \tag{19}$$

holds, where p is the acoustic pressure amplitude, a the amplitude of the particle displacement, ρ the density of the medium, c the speed of sound and ω the angular frequency. Thus the acoustic pressure is known at a point in the acoustic field and, by measuring the voltage generated by a hydrophone placed at that point, a value for the pressure sensitivity can be determined.

Systems differ mainly in their methods of compensating for environmental vibrations, which are a major problem as they cause displacements many orders of magnitude greater than the acoustic displacement being measured (less than 1 nm).

2.3.1 Measurement of acoustic displacement

Although optical interferometric techniques have been widely used for measuring displacements of vibrating objects, it is only in recent years that these techniques have been applied to the measurement of the much smaller displacements caused by an ultrasonic wave travelling in water [60]. This is because of the difficulty of overcoming the problem of environmental vibrations.

Several papers have been published describing the development and progress at the RCA Laboratories (Princeton, New Jersey, USA) of the "Ultrasonovision" system for measuring acoustic wavefronts as part of a technique for producing acoustical images. Several of these papers cover similar material and most of the relevant information is contained in [61]-[64]. The interferometer described in these papers was basically a Michelson-type interferometer with a "wiggler" which caused a vibration of the reference mirror at around 25 kHz giving a phase variation of at least 180°. This induced phase variation meant that the phase corresponding to maximum sensitivity (with the reference beam 90° out-of-phase with the signal beam so that the slope of intensity versus phase was steepest) was repeatedly traversed, so that by measuring the peak value of the signal the effect of ambient vibrations was minimised.

The mirror in the signal beam was a thin (6 μm) metallised plastic pellicle that was suspended in water so that the acoustic wave passed through it (see Figure 10). Thus the laser beam could interrogate the acoustic beam at the point on the pellicle on which it was focussed. This point could be scanned across the ultrasound beam by rotating and tilting a system of mirrors.

A minimum measurable displacement amplitude of 0.01 nm is given with a bandwidth of approximately 10 MHz, but it is suggested that the minimum detectable displacement would be 0.7 pm if the minimum bandwidth of the entire system (approximately 50 kHz) were used. There is no discussion or statement of uncertainties, apart from a brief mention of a measurement on a transducer that had been previously calibrated by the US Navy Underwater Sound Reference Laboratory at 1 MHz using an undisclosed technique. The agreement was within ± 5% but no results are given.

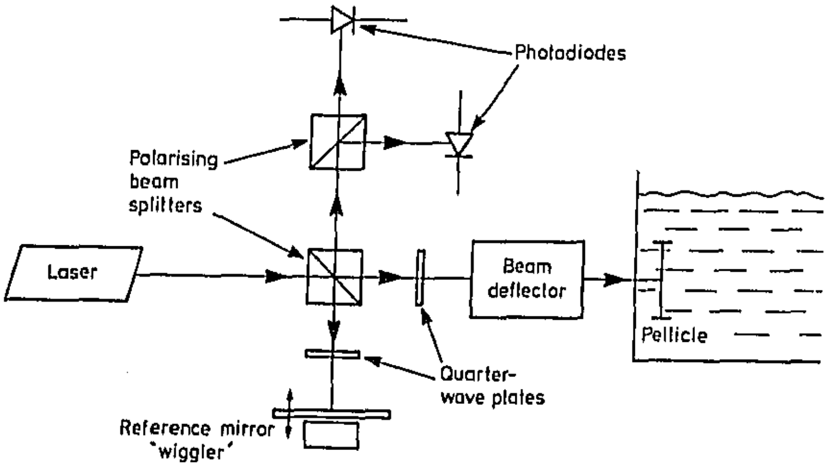

Figure 10 Arrangement of "Ultrasonovision" interferometer.

A later version of the "Ultrasonovision" [63, 64] dispensed with the "wiggler" because it could not measure acoustic pulses shorter than 10 μs. The later system for stabilisation employed a 90° phase shift in the reference beam so that when the two beams were recombined they were in phase-quadrature. By squaring the signals before recombining them it was possible to produce a system with constant sensitivity although it then measured the square of the pressure. Again, no justification is given for the unbelievable claim of an uncertainty of $\pm$ 0.5 dB ($\pm$ 6%) in measurements of 2.5 MHz ultrasound pulses of 1 pm displacement! In fact, this uncertainty value is only mentioned in the abstract of [63] and not at all in the paper itself. From his experience of the "Ultrasonovision" system, Haran [11] suggests that a more realistic value for the minimum detectable displacement is 100 pm which is one hundred times larger than that stated in [61].

In 1978, Speake [65] described the use of an interferometer, designed and built at AERE/Harwell, for the absolute calibration of ultrasonic transducers. This interferometer was also based on the Michelson interferometer but the technique for eliminating ambient vibrations employed an electro-optic cell [66] which, using a feedback system, shifted the frequency of the reference beam by the same amount as the vibrating surface shifted the frequency of the signal beam due to the Doppler effect. A phase-locked loop was formed so that the reference beam tracked the phase of the signal beam and compensated for all the low-frequency vibrations up to a frequency of about 10 kHz. Above this frequency, movements of the vibrating surface were detected without compensation in the reference beam and could be measured with a minimum detectable displacement of 0.01 nm although the bandwidth is not given. The optical arrangement of the interferometer is shown schematically in Figure 11. The laser beam could be focussed to a spot size of less than 0.2 mm in diameter, allowing localised areas of the vibrating surface to be examined with this spatial resolution.

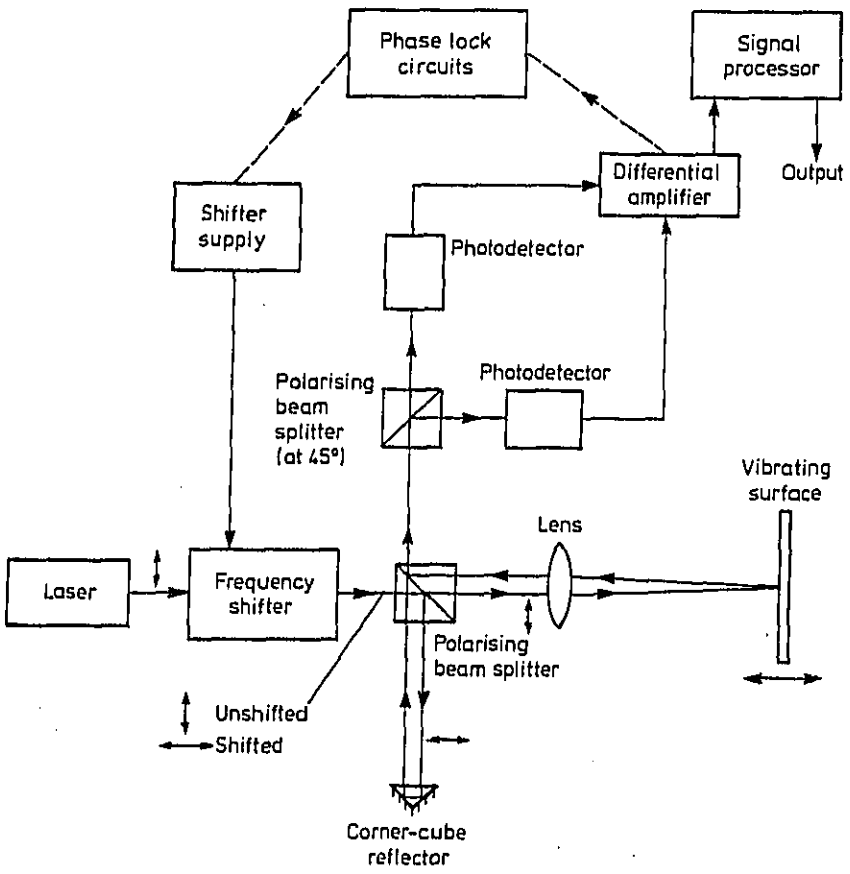

Figure 11 Optical arrangement of the AERE/Harwell phase-locked interferometer.

Baboux et al [67] used an AERE/Harwell interferometer to interrogate the free liquid surface and determine the acoustic displacement. This technique was not used for the calibration of hydrophones and was developed primarily to measure acoustic parameters in the near field of the transducer.

In the system used by the "Ultrasonovision" interferometer [61], the laser beam passed through the acoustic field in the water behind the pellicle, requiring a correction for the effect of the acousto-optic interaction on the refractive index of water. However, this correction was only calculated for plane-wave conditions so, for measurements in the near field, it would be necessary to use either a pellicle and re-calculate the acousto-optic correction or a surface reflection technique such as that of Reibold [59] or Baboux et al [67] and calculate the considerable effect of surface tension. For measurements made in the far field it would be possible to use a pellicle to reflect the laser beam without further calculation of the acousto-optic effect.

Further work by Reibold and Molkenstruck [68] used a laser interferometer to measure displacements comparable with or larger than the wavelength of the laser light by using two interferometric signals in phase quadrature. This was of use for large displacements (> 10 nm) from transducers such as those produced for medical diagnostic scanning. However, this method had a resolution of only 0.5 nm and in any case such large displacements are difficult to produce at frequencies above a few MHz.

Finally, a laser interferometer developed by Nagai and Iizuka [69, 71] used a Bragg cell to split the laser beam and shift the frequency of the reference beam by 30 MHz (f_s). The signal beam was modulated at the ultrasonic frequency (f_m). When the reference and signal beams were recombined, the received signals at the beat frequencies f_s and $|f_s \pm f_m|$ were used to determine the amplitude of the displacement which was causing the modulation of the signal beam.

2.3.2 Hydrophone calibration

Some of the methods described in Section 2.3.1 for measuring acoustic displacement have not been used as techniques for hydrophone calibration. Others used previously-calibrated hydrophones for validation purposes, the results from which are relevant to this review along with the results from the techniques which have been used to calibrate hydrophones.

The "Ultrasonovision" system [61]-[64] was developed at the RCA laboratories primarily to produce acoustical images, hence its ability to scan across a pellicle placed in the field. However, it is possible to replace the pellicle with a hydrophone after measuring the displacement at a point in the field, thus determining the absolute sensitivity of that hydrophone. Harris et al [70] reported the use of this method to provide an absolute calibration of several hydrophones. No discussion of uncertainties, measurement set-up or procedure is given, so it is not possible to evaluate its usefulness compared with other methods.

Reibold and Molkenstruck [72] used a laser interferometer with the signal beam incident on a pellicle consisting of 6 μm thick aluminium foil stretched across a ring placed on the surface of the water. This meant that no correction for the acousto-optic interaction was required because the optical beam did not pass through any water. Fourier analysis of the signal obtained using a short acoustic pulse was used to compare the output-voltage spectrum from the hydrophone with the acoustic-velocity spectrum (obtained from the derivative of the displacement with time) from the interferometer. No absolute values of sensitivity are given but the frequency responses of three types of hydrophone were compared between 0.5 and 3 MHz. The resolution was limited (probably by the digitisation sampling increment) to 1 nm. There seems to have been no stabilisation system. No other uncertainties are stated nor was there a comparison with any other calibration technique.

Nagai and Iizuka [71] used a hydrophone which had been previously calibrated by the manufacturer (Mediscan Inc), using an unspecified technique and with unknown accuracy, to validate their interferometric technique. According to Fischella and Carson [50], Mediscan calibrated their hydrophones using a sphere radiometer (see Section 2.5). Nagai and Iizuka used a plastic film pellicle as an optical reflector and, as with the "Ultrasonovision" system, it was mounted vertically in the tank with the ultrasound being transmitted along a horizontal axis. An accuracy of ± 20% is suggested for their technique, this figure being derived from the repeatability of the determination of total output power using diametrical scans across the pellicle in the acoustic field. Agreement with the hydrophone was within ± 10% for the measurement of peak displacement.

The optical phase-locked interferometer developed at AERE/Harwell and described by Speake [65] and by Drain et al [73] was further developed, specifically to calibrate hydrophones, by AERE/Harwell in consultation with NPL under a contract partially supported by the European Economic Communities, Bureau Communitaire de Reference (BCR). NPL was responsible for defining and verifying the performance specifications, for applying the device to the calibration of hydrophones, and for studying the sources of systematic and random uncertainty in the calibration technique. The most complete description of the system, treatment of uncertainties and validation of the technique can be found in the final reports of the BCR contract [74] and [75]. Other papers dealing with the system and its performance are by Preston et al [41], Bacon et al [76] and Preston [77].

The interferometer used a thin pellicle of either 5 µm or 3 µm thick mylar with a thin gold coating. As the mount in the water tank was designed for calibrating PVDF membrane hydrophones [8], the pellicles were made to the same dimensions as the hydrophones. Thus, during calibration, it was easy to replace the hydrophone with the pellicle after aligning the laser spot on the active element of the hydrophone. Calibrations were made in the far field of the transducers so the plane-wave correction for the acousto-optic interaction could be used. Figure 12 shows the interferometer schematically. The uncertainties have been very thoroughly assessed for this technique as it is used as a primary standard. The overall uncertainties (95% confidence level) range from ± 2.1% at 0.5 MHz to ± 3.4% at 10 MHz and ± 6.3% at 15 MHz. The largest contribution to these uncertainties was from the determination of the frequency response of the photodiode detectors; it is hoped to have these re-calibrated and thus reduce the uncertainties. The interferometer at NPL has been intercompared with the reciprocity and planar scanning techniques and agreement was satisfactory when all the results were corrected to a water temperature of 20 °C. This intercomparison is discussed in greater detail in Section 4.1. The results of the calibration using the interferometer were also in agreement, within the uncertainties, with the theoretical membrane hydrophone frequency-response model of Bacon [78], see Figure 13.

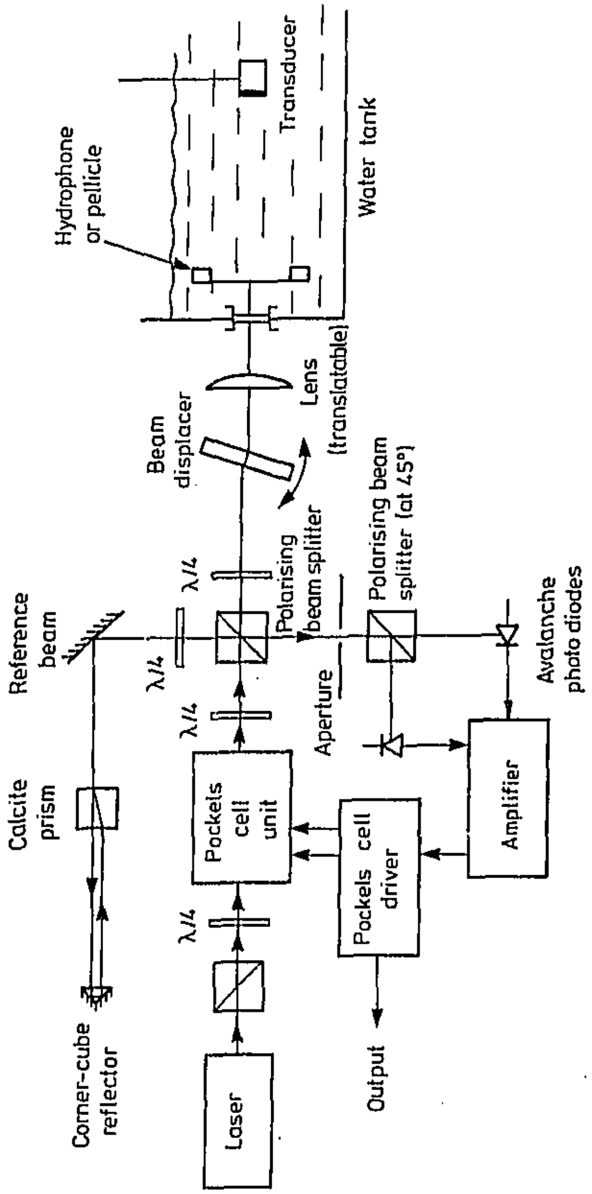

Figure 12 Schematic diagram of the interferometer used at NPL for hydrophone calibration.

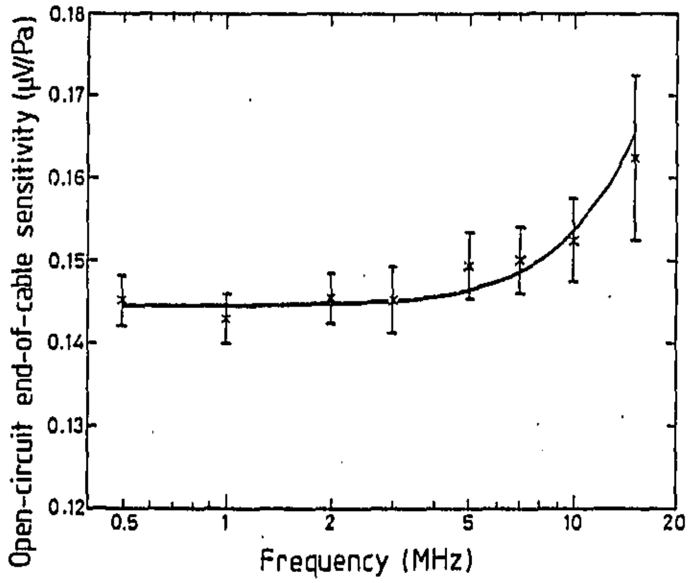

Figure 13 Interferometer calibration values for a 25 μm coplanar shielded PVDF membrane hydrophone compared with Bacon's theoretical frequency-response model [78] (solid line).

2.4 Nonlinear propagation technique

This technique uses the sawtooth acoustic waveform produced by finite-amplitude distortion due to the nonlinear propagation of ultrasound in water. The rate of decrease in amplitude with axial distance depends on the initial amplitude. It is therefore possible to determine this amplitude by measuring the variation of the output voltage from a hydrophone placed in the field of a projecting transducer as the drive voltage is varied. Knowing the initial amplitude, it is possible to calculate the amplitude and frequency content at a point in the field, enabling a hydrophone placed at that point to be calibrated by Fourier analysis of its output signal (see Figure 14). The main advantage of this technique is its ability to calibrate hydrophones at frequencies up to 70 MHz, well above the limit of other techniques (approximately 15 MHz).

There are only two known papers dealing with this technique, which

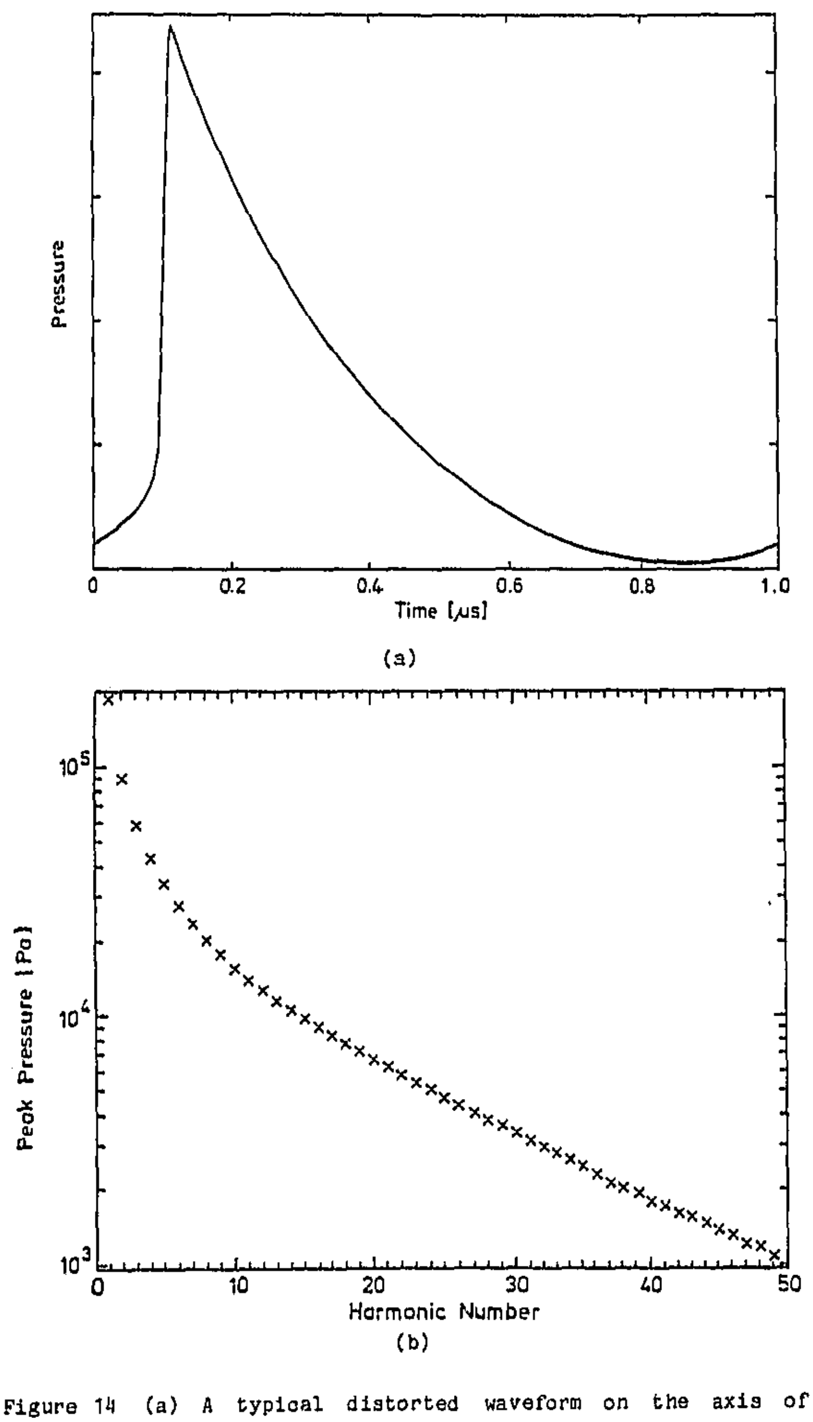

Figure 14 (a) A typical distorted waveform on the axis of a transducer driven at 1 MHz. (b) The harmonic content of such a waveform.

was devised by Bacon at NPL. The first of these [78] derives a theoretical frequency-response model for membrane hydrophones based on known properties of PVDF film. An early version of the absolute calibration technique was used to test the theory between 0.5 and 15 MHz with the conclusion that good agreement with theory can be achieved if the piezoelectric voltage coefficient is assumed constant with frequency. This theoretical model was useful for the second paper by Bacon [79], which describes the absolute calibration technique, as there was no other valid calibration technique above 15 MHz. The second paper gives the theoretical calculation method for determining the frequency content at a point in the nonlinear acoustic field. Also given are calibration results using a 1 MHz fundamental for frequencies from 1 to 14 MHz, a 2 MHz fundamental for frequencies from 2 to 28 MHz and a 5 MHz fundamental for frequencies from 5 to 70 MHz. These results were combined and compared with reciprocity and planar scanning calibrations up to 15 MHz and were found to agree to well within the stated uncertainties. The results of this comparison are shown graphically in Figure 23 (see Section 4.1). The theoretical frequency-response model described above was compared with this technique and agreement was within ± 5% right up to 70 MHz (see Figure 15). These two comparisons were sufficient to validate the technique; the estimated uncertainty was approximately ± 15%.

No other attempt to employ this calibration technique has been reported despite the importance of knowing the frequency response of hydrophones up to over 70 MHz for measurements on pulsed medical diagnostic equipment [9, 10].

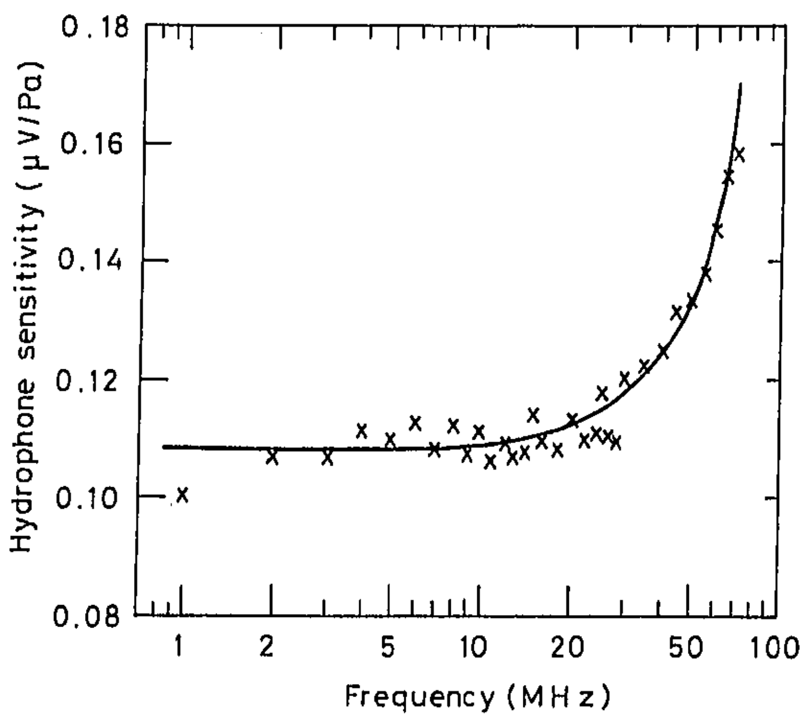

Figure 15 Comparison of the results of the nonlinear method (x) with Bacon's theoretical frequency-response model [78] (solid curve).

2.5 Radiation pressure on a small sphere

The existence of a radiation pressure proportional to the mean energy density in an acoustic wave is well documented in the literature. Large targets which intercept the whole beam, and therefore measure the total power, are commonly used and some of these are mentioned in Section 2.2. It is also possible to map the distribution of energy within a beam by using a small target such as a sphere suspended in pendulum fashion (see Figure 16).

Knowing the effects of reflection from a small sphere, the displacement of the target d due to the radiation force F_r can be used to determine the local acoustic intensity I using the following two equations:

$$F_r = \frac{mgd}{(L^2 - d^2)^{1/2}} \qquad (20)$$

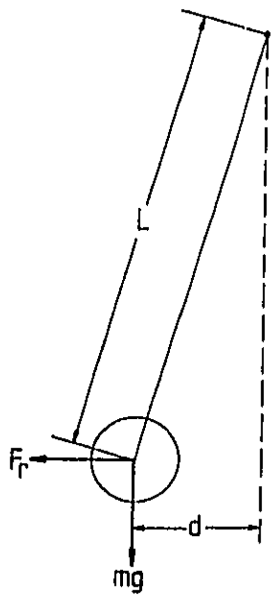

Figure 16 Forces acting upon a sphere suspended in a sound field.

$$I = \frac{F_r\ c}{\pi a^2 Y} \qquad (21)$$

where Y is the radiation force per unit cross section per unit energy density, a dimensionless constant known as the acoustic radiation force function. It is the calculation of this acoustic radiation force function Y which has attracted a large amount of effort from researchers in order to find the most suitable size and material for the sphere.

2.5.1 Measurement of acoustic intensity

One of the earliest attempts to solve the problems involved in determining the effects of radiation pressure on small spheres was presented in 1934 by King [80]. He produced a well-respected and frequently-referenced theoretical analysis of the effect on a rigid sphere in a frictionless medium. The assumption of these ideal conditions was to enable orders-of-magnitude calculations to be made and to assist the design of torsion balances for optimum sensitivity. He correctly stated that, if such instruments proved suitable for sound measurement, it would be possible to extend his analysis to include the compressibility of the sphere and the viscosity of the medium. In fact that was exactly what happened. King developed the following equation for the mean radiation pressure over the sphere $\overline{P}$ for spheres of radius a, small in comparison to the wavelength, and for plane progressive waves:

$$\frac{\overline{P}}{a^2} \simeq 4(ka)^4 f(\rho_o/\rho_1)\overline{E} \qquad (22)$$

where $\overline{E}$ is the mean energy density, k is the wavenumber ($=2\pi/\lambda$) and $f(\rho_o/\rho_1)$ is the relative density factor given by:

$$f(\rho_o/\rho_1) = \frac{1 + \frac{2}{9}(1-\rho_o/\rho_1)^2}{(2 + \rho_o/\rho_1)^2} \qquad (23)$$

where ρ_o is the density of the medium and ρ_1 the density of the sphere.

In 1940, Fox [81] used King's theory to compute the relevant constants for spheres with radii of the order of a wavelength (ka from 1 to 20). He also claimed that the method could be extended to obtain values of the constants for any size of sphere with an accuracy of better than $\pm$ 1%, although at this stage no experimental verification had been given. The theoretical analysis was extended by Faran [82] in 1951 to take into account both shear waves and compressional waves which can exist in solid scatterers. Computed scattering patterns were verified by experimental measurements made using metal cylinders in water, although no measurements were made on spheres. In 1957, Maidanik [83] made use of a general formulation derived by Westervelt [84] to compute a general expression for the force exerted on a scattering sphere by a plane progressive wave. Numerical results were calculated for both 'hard' and 'soft' spheres and it was concluded that there could be advantages in using a 'soft' sphere for measuring the absolute intensity of acoustic fields in liquids because the force is several times greater and the variation of the force with ka is smoother.

Yosioka et al [85] investigated the effect of plane waves on steel spheres in comparison with King's theory [80] and on liquid spheres using their own theory for compressible spheres. Experimental evidence is given showing that the results obtained using steel spheres were larger than those obtained using liquid spheres by 8.5 $\pm$ 3%. The authors suggest that the true acoustic intensity level was rather closer to the value calculated using the liquid spheres as the variation between the measurements was essentially independent of either the frequency, the radius of the liquid spheres or the temperature; also because there is distinct evidence of departure from King's theory for the steel spheres due to elastic vibration. Hasegawa and Yosioka [86] produced a theory to take account of this elasticity and obtained experimental evidence to validate its use in preference to King's theory.

Dunn et al [87] published experimental results showing that, for observations avoiding the resonance minima of the radiation force function Y (see Figure 17), acoustic intensity could be determined to an accuracy of approximately ± 3% if the value of Y was calculated using the theory of Hasegawa and Yosioka [86].

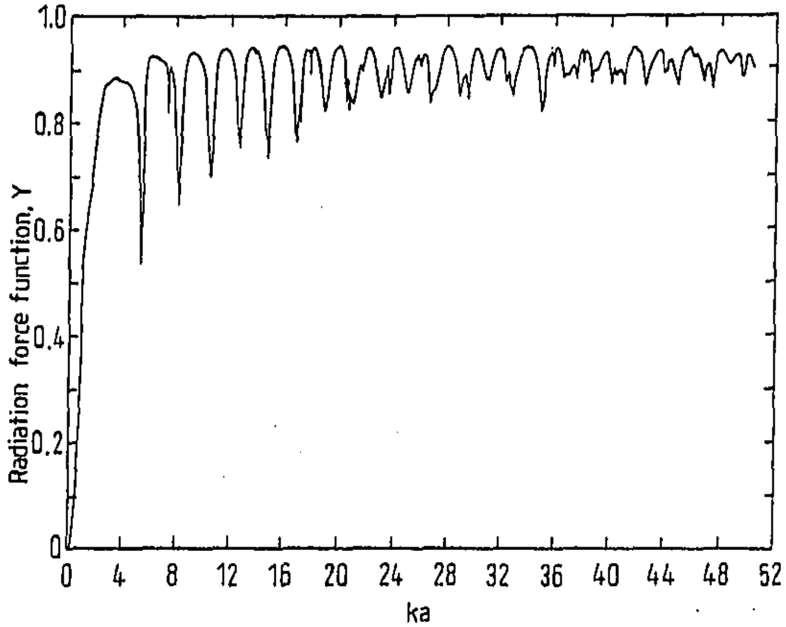

Figure 17 Radiation force function Y, as a function of ka for type 440C stainless steel, where k is the wavenumber and a the radius of the sphere, as determined by Dunn et al [87].

Further work by Hasegawa and Yosioka [88] using fused silica spheres made possible the determination of ultrasonic intensity and calibration of ultrasonic probes with uncertainties of less than ± 2%. Anson et al [89, 90] and Chivers and Anson [91] have investigated sources of error caused by inaccuracies in the value of the sound velocity, density and temperature of the spherical target. They have also considered the effect of the mounting configuration and suspension of the sphere, finding that these problems greatly overshadowed inaccuracies in the calculation of Y. These authors have shown that a more suitable material for the sphere would be alumina, boron carbide or polyethylene as these materials have widely-spaced, shallow minima in the curve of Y against ka. The use of these materials could enable an accuracy of ± 0.1% in the calculation of Y at a single frequency and better than ± 1% over a range of frequencies.

2.5.2 Calibration of hydrophones

When calibrating a hydrophone using this method it is necessary to place the hydrophone far enough from the transducer for the plane wave approximation of intensity to be valid [14] because the sphere radiometer measures acoustic intensity whilst a hydrophone measures acoustic pressure.

Although this technique has been widely used to determine acoustic intensity, and accuracies of better than ± 2% have been claimed, there is little information in the literature about the use of this method for the calibration of hydrophones. In 1973, Herman et al [49] reported an attempt to calibrate a ceramic probe hydrophone at 1 MHz using this method. The displacement of the sphere was measured using a travelling microscope and the intensity was calculated for ten different points on the acoustic axis of a transducer. At each point the sphere was replaced by the hydrophone to obtain the calibration. The results of all ten calibrations are presented and the random uncertainty was ± 7% (95% confidence limit). The mean value for the hydrophone sensitivity agreed, within the uncertainties, with a value obtained using planar scanning.

Fischella and Carson [50] used ceramic probe hydrophones manufactured by Mediscan Inc who had previously calibrated the hydrophones using this technique. The values from the calibration are given but, on intercomparison with total power measurements, large discrepancies of up to 300% were found; this is probably attributable to limitations in hydrophone design rather than the accuracy of the calibration. Nagai and Iizuka [71] also used Mediscan hydrophones (see Section 2.3.1) and calibrated them using an optical interferometer; agreement with the manufacturer's calibration using the sphere radiometer technique was within ± 10%.

Dunn and Fry [92, 93] used a steel sphere radiometer to provide an absolute calibration of a thermocouple probe over the frequency range 0.5 to 10 MHz. The only uncertainty value given is ± 2.5%, which appears to be a standard deviation obtained from a least-squares fit to the calibration values. Palmer [94] also used a suspended steel sphere as a standard to compare measurements made with thermoelectric detectors; he used Fox's [81] expression to determine the intensity of the radiation.

2.6 Thermoelectric techniques

Absorption of ultrasonic energy resulting in heating of the transmission medium causes a temperature rise which can be measured using a suitably small thermoelectric detector. From the temperature rise, a knowledge of the specific heat capacity and the absorption coefficient of the medium, it is possible to obtain an absolute value for the acoustic intensity. The conversion of mechanical (sound) energy into thermal energy results from several mechanisms but, at the low-megahertz frequencies used for medical applications and with the ultrasound travelling in water, viscous losses dominate over the other mechanisms. Two types of thermoelectric receiver have been used to resolve the spatial distribution of acoustic intensity in an ultrasound beam, namely thermistors and thermocouples. Various probes have been designed to contain the receiver whilst being transparent to the ultrasound and having a calculable heat capacity or incorporating a heater for calibration purposes.

2.6.1 Measurement of acoustic intensity

In 1953, Palmer [94] made a probe using four thermocouple junctions on the end of a hyperdermic needle which was covered with a sound-absorbing substance. Many substances were tried and paraffin wax proved to be the most sensitive, giving the largest temperature rise for a given incident intensity. This device needed to be calibrated against a standard and in this case a suspended steel sphere was used (see Section 2.5.2). In 1954, Fry and Fry [95] produced a detailed theoretical analysis of the operation of thermocouple probes embedded in a sound-absorbing medium of similar specific acoustic impedance to the transmission medium. This provided a sound theoretical basis for other workers in the field to draw on when designing probes and estimating sources of systematic uncertainty such as the finite heat capacity of the thermocouple wires, heat conduction between the thermocouple and the fluid and viscous forces between the thermocouple and the embedding medium. The formula fundamental to the determination of absolute acoustic intensity I is:

$$\mu I = \rho C(dT/dt)_o \qquad (24)$$

where μ is the acoustic intensity absorption coefficient per unit path length in the embedding medium of density ρ and specific heat capacity C, and $(dT/dt)_o$ is the initial rate of temperature rise immediately after the transducer was switched on.

Fry and Fry [95] and Dunn and Fry [93] described a thermoelectric probe produced by embedding a thermocouple in a sound-absorbing medium which was separated from the transmission medium by thin (80 μm) polyethylene sheets stretched across an annulus having an aperture large enough to transmit the whole sound beam (see Figure 18). When a one-second toneburst of ultrasound was applied to this thermocouple probe, the deflection of the galvanometer was similar to that shown in Figure 19.

The initial rise in temperature was due to the action of viscous forces between the fluid medium and the wire. The second phase of the deflection, the 'linear' part, was a result of absorption of sound in the body of the fluid medium and it was the slope of this part of the deflection curve which was used to determine the acoustic intensity. The value was found to be proportional to the square of the driving voltage to the transducer, showing that it is proportional to intensity if the transducer is linear and the measurements are made in the far field. Once again the probe required calibration against a steel sphere radiometer because of the absence of sufficiently-accurate values for the acoustic absorption coefficient of the castor oil embedding medium.

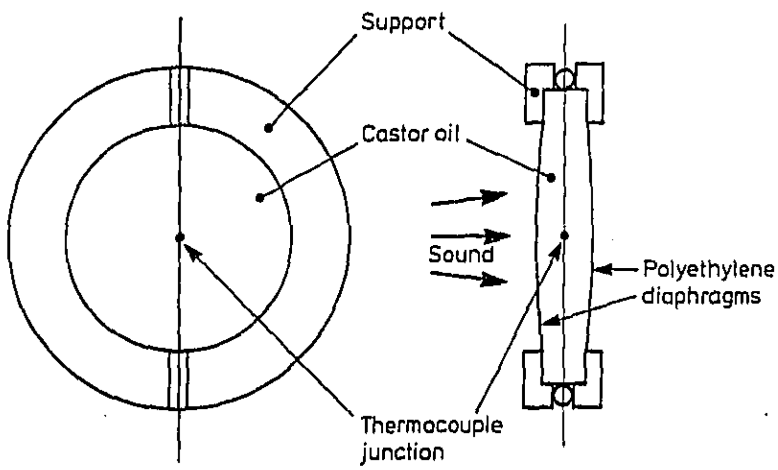

Figure 18 Schematic diagram of the thermoelectric probe produced by Fry and Fry [95].

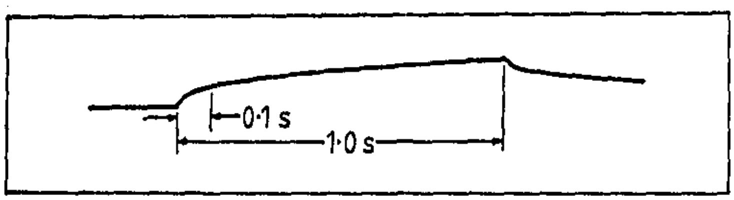

Figure 19 Galvanometer deflection for a one second toneburst incident on a thermocouple embedded in castor oil.

A semi-conducting thermistor was used by Labartkava [96] as the sensing element of his probe, which consisted of a hollow glass sphere filled with semi-conducting material and coated with a thermo-sensitiser material. The thermistor was wired into a balanced dc bridge circuit. This probe also needed calibration against other standards.

Another probe using a thermistor was reported by Howard and Galle [97] but this did not produce absolute measurements either.

2.6.2 Hydrophone calibration

Colbert et al [98] have used one of the thermoelectric probes described by Fry and Fry [95] to calibrate a hydrophone. The thermoelectric probe had been calibrated using a one-second toneburst, so the hydrophone calibration was only valid when substituted for the thermoelectric probe in such a toneburst. The uncertainty in the calibration was estimated to be $\pm$ 1% but this seems to be a very optimistic value.

Due to a lack of accurate information about the ultrasonic absorption coefficient of absorbing media, this type of measurement has not been fully validated for accurate hydrophone calibrations. Although work is continuing on the measurement of absorption in such materials, it is unlikely that this technique will produce accurate absolute measurements of acoustic intensity in the future unless absorbing media can be found which have a better long term stability than castor oil.

2.7 Pulse techniques

Various attempts have been made to determine absolute values of acoustic field parameters and to calibrate hydrophones by using pulses or step functions to drive a transducer. However, it is not always clear whether a particular method is truly absolute or not and for this reason some of the pulse techniques appear in Section 3.3.

2.7.1 Measurement of acoustic pressure

In 1977, Perdrix et al [99] described a technique for calculating the acoustic pressure near to the face of a thick piezoelectric disc excited by a short impulse current $i(t) = Q\delta(t)$ (where $\delta(t)$ is the Dirac δ-function). This produced a pressure step, and waves with a particle velocity v proportional to the charge Q moved by the current impulse appeared at the two transducer faces:

$$v(t) = \frac{dQ}{(\rho c + \rho_1 c_1)A} \, u(t) \qquad (25)$$

where d is the piezoelectric charge coefficient, ρc is the acoustic impedance of the medium and $\rho_1 c_1$ the acoustic impedance of the disc, A is the area of the disc perpendicular to the acoustic axis and u(t) is the Heaviside step function.

Then Perdrix et al used the relationship that the amplitude of the pressure step P_o (ie $p(t) = P_o u(t)$) is equal to the acoustic velocity amplitude multiplied by the specific acoustic impedance of the medium, giving:

$$P_o = \frac{\rho c d Q}{(\rho c + \rho_1 c_1)A} \qquad (26)$$

The wave from the rear face of the transducer propagated through the disc and caused a pressure step of smaller amplitude and opposite sign at some later time. Thus the reverberations in the transducer appeared as a series of pressure steps of decreasing amplitude. No mention is made of how the piezoelectric charge coefficient was measured and whether it was frequency dependent; this is an important aspect of an absolute technique because it is precisely this measurement which determines the sensitivity of a transducer. Another factor is the effect of the edge-wave and plate-wave pulses which arrive a short time after the main pulse and must be outside the time window used.

Pesqué and Méquio [100] have also used a theoretical model to calculate the acoustic pressure spectrum at a point in the far field of a specially-designed transducer with characteristics that are easy to model theoretically. The calculation involved the determination of the Laplace transform of the particle velocity V(s) at the transducer surface, which was derived from the generator voltage transform E(s) and the transmitting transfer function T(s). The latter was calculable, for given reflection and transmission coefficients between the transducer layers, from a knowledge of the piezoelectric charge coefficient and other coefficients for the transducer, but these may be frequency dependent and are themselves difficult to measure. The following relationship was obtained:

$$V(s) = T(s).E(s) \qquad (27)$$

where s is a Laplace variable. An inverse Laplace transform gives the velocity v(t) and from this the velocity potential $\phi(\underline{r},t)$ can be calculated from the convolution:

$$\phi(\underline{r},t) = v(t) * h(\underline{r},t) \qquad (28)$$

where $h(\underline{r},t)$ is the diffraction impulse response of a piston embedded in an infinite and rigid plane baffle and has been dealt with by Stepanishen [101]. From the velocity potential ϕ it is possible to derive the acoustic pressure p at a point:

$$p(\underline{r},t) = \rho(\partial/\partial t)\,\phi(\underline{r},t) \tag{28}$$

where ρ is the density of the medium. The pulsed pressure field transmitted from a circular transducer can, therefore, be calculated using a knowledge of the transducer materials. This is an ingenious method for determining absolute acoustic quantities but it does rely heavily on the transducer behaving as a perfect circular plane piston and on the knowledge of several coefficients for the transducer which may be frequency dependent and which themselves must be determined using another absolute method.

A transducer conforming to the theory was built and the method tested by comparing the pulse-echo from a steel mirror placed close to the transducer with a corresponding simulated echo. The cross-correlation function had a maximum value of 98%, which showed good agreement with theory. Further verification of the technique was achieved by finding, from the spectrum at a given point on the acoustic axis, the frequency at which zero pressure occurred and comparing this with the expected value from the theory. Agreement was good in the example given, confirming that the transducer did indeed behave as a piston source. Directivity measurements in both impulse and toneburst excitation were also performed, the use of a short pulse from the transducer permitting a broad spectrum of frequencies to be covered. The frequency-dependent attenuation of ultrasound in water had to be taken into account in these calibrations.

2.7.2 Hydrophone calibration

Both of the methods described in Section 2.7.1 have been used to produce absolute calibrations of hydrophones with some success.

Perdrix et al [99] placed three different hydrophones close to a thick piezoelectric disc and, by taking a fast Fourier transform, obtained their receiving sensitivities. The only experimental results shown are photographs from a spectrum analyser display; plotted on one of these are points which represent reciprocity calibrations obtained at another laboratory but the exact technique used is not described. The results seem to be in agreement to within ± 2 dB over a frequency range of 1 to 6 MHz but the presentation of the results is not very clear; no uncertainties are mentioned. Thus, this has not been validated as an absolute technique but it has been shown to be useful as an intercomparison technique for the 1 to 20 MHz range.

The technique described by Pesqué and Méquio [100] was used to calibrate two types of hydrophone using a 5 MHz transducer. Firstly a Nuclear Associates PVDF needle probe hydrophone was calibrated from 1 to 7 MHz. Secondly a Lewin PVDF needle probe hydrophone [6] was calibrated from 1 to 7 MHz and the results compared with the manufacturer's calibration chart which had been obtained using reciprocity and time delay spectrometry [102]. The two calibrations agreed to within ± 1 dB (± 12%) and from this the authors assigned a measurement uncertainty of ± 15%. This technique was relatively rapid and provided a calibration over a wide frequency range (1 to 7 MHz) simultaneously.

3. CALIBRATION BY COMPARISON WITH A STANDARD HYDROPHONE

Comparison techniques for the calibration of hydrophones are widely used as methods for disseminating the absolute calibration of a standard hydrophone. They have advantages over the absolute techniques (described in Section 2) of rapidity and simplicity whilst having the disadvantage of introducing an additional source of uncertainty from the intercomparison.

3.1 Discrete frequency method

The basic principle is to place each of a group of hydrophones, including at least one standard hydrophone, at an identical position in the far field of an ultrasonic transducer which is being driven by short tonebursts of a single frequency (using a toneburst avoids problems of electrical interference or reflections in the tank). The output voltage from each hydrophone is measured and the ratio of the sensitivity of each hydrophone to the sensitivity of the standard hydrophone derived. In the absence of plane waves, a correction is required for any difference in size of the elements of the standard hydrophone and the hydrophone being calibrated. This correction can be obtained from the curves produced by Fay [36] which are shown in Figure 5. A second correction converts the end-of-cable sensitivity to the end-of-cable open-circuit sensitivity using equations (1) to (4) in Section 1.

Presumably due to the simplicity of this technique, very little has been published in the literature to describe variations in method or accuracies. The method used at NPL was very briefly described by Preston et al [8] and the standard error on the mean for the intercomparison is quoted as ± 2.5% at all frequencies. At NPL many hydrophones are calibrated using this technique which is offered as a measurement service. Two standard hydrophones are used in each group of hydrophones. For each frequency, measurements are performed at two and three times the near-field distance of two different transducers (four measurements in all). Care is taken to minimise finite-amplitude distortion in the received wave by keeping the peak acoustic pressure down to a suitable level. To reproduce the same position in the acoustic field, the signal from each hydrophone is maximised using two translational and two rotational degrees of freedom to ensure it is on the axis of the beam and orientated correctly. The time delay from the transducer excitation pulse to the received signal is also checked. The total systematic uncertainty in the intercomparison is estimated to be less than ± 5% over the frequency range 0.5 to 15 MHz (95% confidence limit). The random uncertainty in the intercomparison is estimated to be less than ± 3% at all frequencies (95% confidence limit) and this has been verified by checking the ratios of the sensitivities of the two standard hydrophones on 20 occasions over a period of two years.

The disadvantage of the additional uncertainty introduced into the calibration of the hydrophone due to the comparison with a standard hydrophone must be offset against the rapidity of measurements. However, several improvements have been suggested which can increase the speed of measurements without increasing the uncertainties significantly and these are covered in the following sections.

3.2 Use of a distorted waveform

The technique of using a distorted waveform was first described and used by Bacon [78] for the investigation of a theoretical model for the frequency response of a membrane hydrophone. It was used in conjunction with the more complex absolute technique [79] (see Section 2.4) to determine the sensitivity of a hydrophone up to 100 MHz. The method is to place each of a set of hydrophones, including at least one standard hydrophone which has been calibrated absolutely, sequentially at the same point in an acoustic field at which the waveform displays significant finite-amplitude distortion due to the nonlinear propagation of ultrasound in water. The resultant waveform, shown in Figure 14 in Section 2.4, is received by each hydrophone and their outputs digitised. A fast Fourier transform is then performed and the amplitude of each harmonic component in the output spectrum compared with the corresponding amplitude from the standard hydrophone. Thus, ratios of sensitivities relative to the standard are obtained at frequencies which are multiples of the fundamental which is most conveniently 1 MHz. It is possible to maintain reasonable signal-to-noise ratios up to over 20 MHz by using appropriately-designed transducers producing high acoustic pressures. To avoid overheating of the transducer, a toneburst signal is used with a very low repetition rate (less than 150 Hz). A schematic diagram of the equipment is shown in Figure 20.

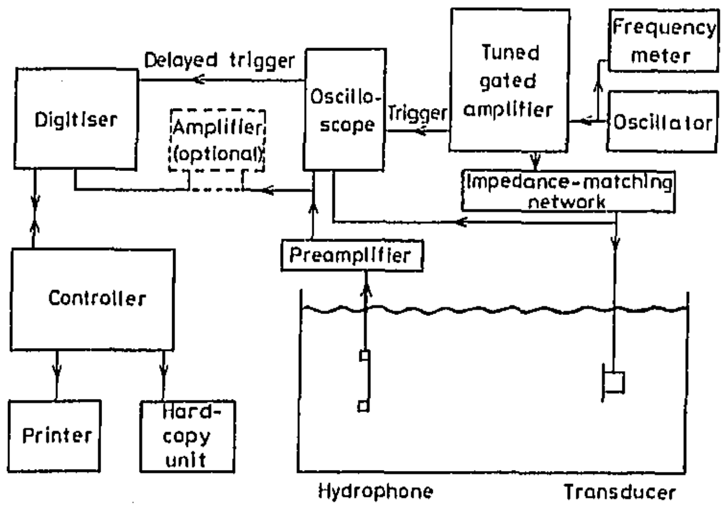

Figure 20 Schematic diagram of the experimental apparatus for the distorted waveform intercomparison technique (after [79]).

Since the papers by Bacon [78, 79] (see Section 2.4), more work has been done at NPL to validate the technique as a means of calibrating customer's hydrophones. Results suggest that the ratios obtained from this technique agree with those for the discrete frequency method (Section 3.1) to within ± 4%, and the estimated random uncertainties are less than ± 3% (95% confidence level) for the frequency range 1 to 8 MHz, less than ± 5% for the frequency range 9 to 12 MHz and less than ± 8% for the frequency range 13 to 15 MHz. The systematic uncertainties at the 95% confidence level range from ± 5% at 1 MHz to ± 8% at 15 MHz. The technique was used to calibrate a variety of hydrophones including:

0.5, 1 & 2 mm diameter coplanar shielded PVDF membranes [8]
0.5 and 1 mm diameter bilaminar shielded PVDF membranes [8]
1 mm diameter PVDF needle probes from two manufacturers [6]
0.2 and 0.6 mm diameter ceramic needle probes [5].

The standard hydrophone was a 1 mm diameter coplanar shielded PVDF membrane hydrophone which had been calibrated using the interferometric technique [75, 76]. Some results from this validation exercise are plotted in Figure 21 and a paper is in preparation, covering the validation of the technique and giving a full treatment of uncertainties.

Early results showed larger random uncertainties at 1 and 2 MHz and a lack of smoothness in the measured frequency response at the lower end of the frequency range. This could be caused either by distortion in the transient digitiser, a Tektronix 7912AD which is known to suffer from "pincushion" distortion, or by glancing reflections from the sides of the tank. The system now used at NPL employs a digitiser which does not suffer from this type of distortion and improved baffles have been fitted along the tank sides to prevent reflections. The problem at the lower frequencies does not exist on the new system as can be seen in Figure 21.

Obvious advantages with this method of hydrophone calibration are: the rapidity of measurements, the inclusion of frequency points at all multiples of 1 MHz up to over 15 MHz and the possible extension of the technique to even higher frequencies if required. Other advantages include: the ability to align the hydrophone in the acoustic field more precisely by using a 40 MHz high-pass filter to increase the directional sensitivity of the hydrophone, the lack of any G_2 corrections for the finite size of the hydrophone (because measurements are made at distances from the transducer where the correction is negligible [36]) and finally the ability to automate the data acquisition, processing and storage for all hydrophone calibrations.

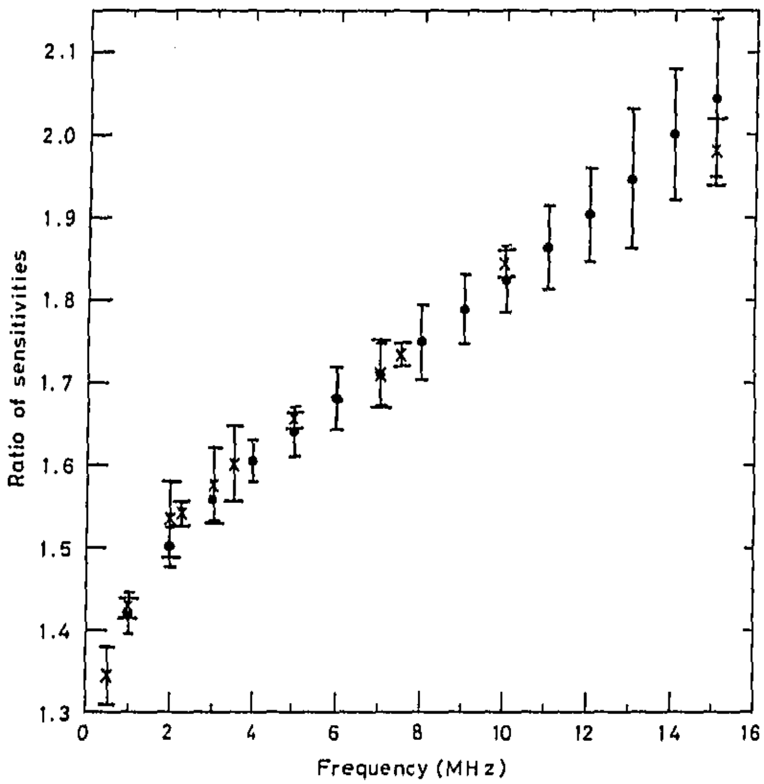

Figure 21 Graph of the ratio of the sensitivity of a hydrophone to that of a standard hydrophone using:

- • the present technique of Section 3.2 and
- x the discrete frequency method of Section 3.1.

The error bars represent random uncertainties at the 95% confidence level (work to be published).

3.3 Pulse techniques

The advantage of a technique using a pulse of ultrasound over the discrete frequency method is the ability to intercompare hydrophones over a range of frequencies simultaneously. In this aspect the technique is similar to that described in Section 3.2. Two pulse techniques have already been dealt with in Section 2.7 because they were described as absolute calibration techniques. However, they also have the potential to be used as rapid intercomparison techniques if another, more accurate, absolute technique is available.

Harris et al [70] described a technique where a shock excitation voltage was applied to the transducer to produce a broad-band pulse. By spectral analysis of the hydrophone response it was possible to compare the sensitivity of a hydrophone with that of a standard hydrophone. In fact, the technique could be taken further by replacing the hydrophone with an air-backed mylar membrane and comparing the drive-voltage spectrum with the spectrum of the received signal after reflection. By assuming that the transmitting and receiving responses of the transducer are the same, the spectrum of the pulse incident on the hydrophone could be calculated. Thus, the frequency response of the hydrophone could be determined over a frequency range from 0.5 to 5 MHz using a 2.25 MHz transducer and the discrete frequency comparison (or an absolute calibration) at just one frequency.

The main assumptions in this technique were that the transmitting and receiving responses were the same and that the spectrum of the pulse did not vary with distance from the transducer as a result of diffraction. The latter assumption was required because the reflector was placed at the same distance as the hydrophone so the pulse travelled twice the distance for the pulse-echo case. Also, unless there was plane-wave propagation, the different sizes of the transducer and hydrophone would need to be corrected for. The plane-wave condition only applies near to the transducer face, and is only valid for transducer-hydrophone separations which are small compared with the size of the transducer. Harris et al have given no indication of the actual separation used between the transducer and the hydrophone or reflector. Another unmentioned consideration is the edge-wave pulse which would arrive at the hydrophone shortly after the plate-wave pulse. The delay between pulses would have to be sufficient for them not to overlap, otherwise the plane-wave condition would no longer be valid. Thus, it is necessary for the hydrophone to be placed close to a relatively large-diameter transducer.

In a later paper, Harris et al [103] used a transducer of thickness 25 mm and of diameter 63 mm and a different technique; for this transducer the transmitting response was assumed to be flat above

30 kHz so that the spectrum of the incident pulse was assumed to be the same as the drive-voltage spectrum. Frequency-dependent attenuation was corrected for, but the technique still assumed plane waves to be incident on the hydrophone and no value for the transducer-hydrophone separation is given. Although this technique provided a more rapid hydrophone calibration over a wide range of frequencies, no comparison with other techniques has been reported and no estimate of uncertainties given.

3.4 Time delay spectrometry

A development of the discrete frequency method of Section 3.1 to permit the intercomparison of hydrophones over a continuous frequency spectrum is to drive a broadband transducer with a swept-frequency signal. This would have the advantage of being very rapid to perform whilst maintaining an adequate signal-to-noise ratio. However, there are several problems which prevent the straightforward implementation of this improvement. In a continuous-wave ultrasonic field the hydrophone is subject to ultrasound reflected from the sides of the tank, the water surface and the transducer mounts, and reflections from the hydrophone back to the transducer causing standing waves between the two. Finally the hydrophone, unless it has effective electrical screening, picks up electrical interference from the transducer drive. This is why the techniques so far described all use pulses or short tonebursts of ultrasound.

The technique of time delay spectrometry seeks to overcome these problems, not by using an anechoic water tank but by using a rapid frequency sweep so that a given frequency is defined at an instant in time at the transducer. After a time delay equal to the propagation time, that frequency is also defined at the hydrophone. Thus, the electrical noise and reflections can be removed by filtering the received signal and free-field conditions effectively exist. This is achieved in practice by sweeping the signal using a spectrum analyser.

This technique was proposed by Heyser [104] as a method of measuring the frequency responses of complete audio systems. It has also been used for ultrasonic imaging systems and various diagnostic applications. The only reported implementation of the technique for hydrophone calibration was by Lewin [102], who combined this with absolute calibrations at frequency intervals of 20 and 50 kHz using the reciprocity technique. Lewin used a sweep from 1 to 10 MHz in less than one second. Random uncertainties were reported as ± 0.5 dB (± 6%) and an overall uncertainty was estimated to be ± 1.5 dB (± 19%).

Recently, Filmore and Chivers [105] used this technique to compare ceramic needle probe hydrophones produced in batches. The technique was used alongside another, involving the broad-band excitation of a transducer and the subsequent frequency sweeping of the hydrophone output using an analogue spectrum analyser. The results were apparently very similar but only the time delay spectrometry results are given so it is not possible to compare the techniques quantitatively.

There are various limitations inherent in the time delay spectrometry technique arising from the performance of the spectrum analyser and the difficulty of obtaining a suitable wide-band, temporally-stable transducer. However, these have not been adequately discussed or evaluated in the literature.

4. INTERCOMPARISONS OF CALIBRATION TECHNIQUES

To date there has been no formal international intercomparison of hydrophone calibration techniques, although there may shortly be a BCR-funded European intercomparison with NPL as the coordinating laboratory. However, there have been some informal intercomparisons and also a large amount of work at various standards laboratories involved in the validation of new calibration techniques.

4.1 Absolute calibration

At NPL, the four different absolute calibration techniques that have been used, described in Sections 2.1 to 2.4, have all been intercompared using membrane hydrophones and the results from [41], [75] and [76] are illustrated in Figure 22.

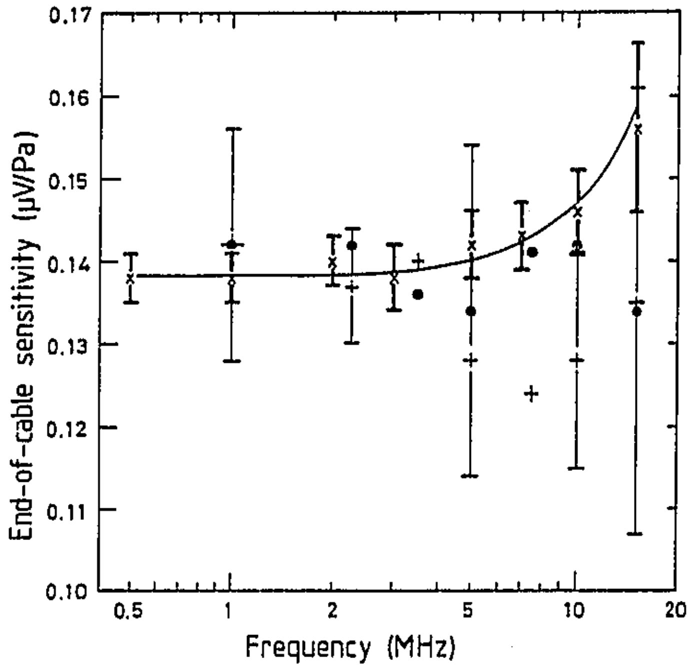

Figure 22 Calibration values determined using:

- • reciprocity;
- + planar scanning and
- x optical interferometry.

The solid curve represents Bacon's model [78].

The values are plotted for the end-of-cable open-circuit sensitivity of a 1 mm diameter, 25 µm thick coplanar shielded membrane hydrophone [8, 41] over the frequency range 0.5 to 15 MHz determined using reciprocity, planar scanning and optical interferometry. Note: the error bars represent the overall uncertainty (95% confidence level) and are given for the interferometer at all frequencies (bold symbols), for planar scanning at 2.25 and 10 MHz and for reciprocity at 1, 5 and 15 MHz. The theoretical frequency response is also shown and is calculated using Bacon's model [78] with the absolute level chosen so that the average sensitivity is equal to that from the interferometer calibration results. As the calibrations were performed at different water temperatures, the sensitivity values have been corrected to 20 °C assuming a temperature coefficient of 0.8% per °C, and the techniques have been found to agree within the measurement uncertainties stated in Section 2. The optical interferometer has now been adopted as the primary standard for hydrophone calibration at NPL.

The nonlinear propagation technique has been intercompared with reciprocity and planar scanning at frequencies from 1 to 15 MHz and with the theoretical frequency response of a 9 µm coplanar shielded membrane hydrophone up to 70 MHz [79]. The results in Figure 23 show that agreement between the techniques was within the measurement uncertainties.

Lewin [6] calibrated a PVDF needle probe hydrophone in 50 kHz steps up to 6.5 MHz using three-transducer reciprocity and in 20 kHz steps up to 10 MHz using two-transducer reciprocity. He also claims that the calibration was independently checked, obtaining agreement within ± 5% up to 7.6 MHz and within ± 11% between 7.6 MHz and 10 MHz, but no indication is given of what technique was used for the third calibration. These values were then compared, via the time delay spectrometry technique, with the planar scanning absolute calibration method at BRH and the results were reported by Gloersen et al [38]. An uncertainty of ± 1 dB (± 12%) was attributed to each technique and tne results in Figure 24 show that the difference in sensitivity at each frequency was less than the reported uncertainty.

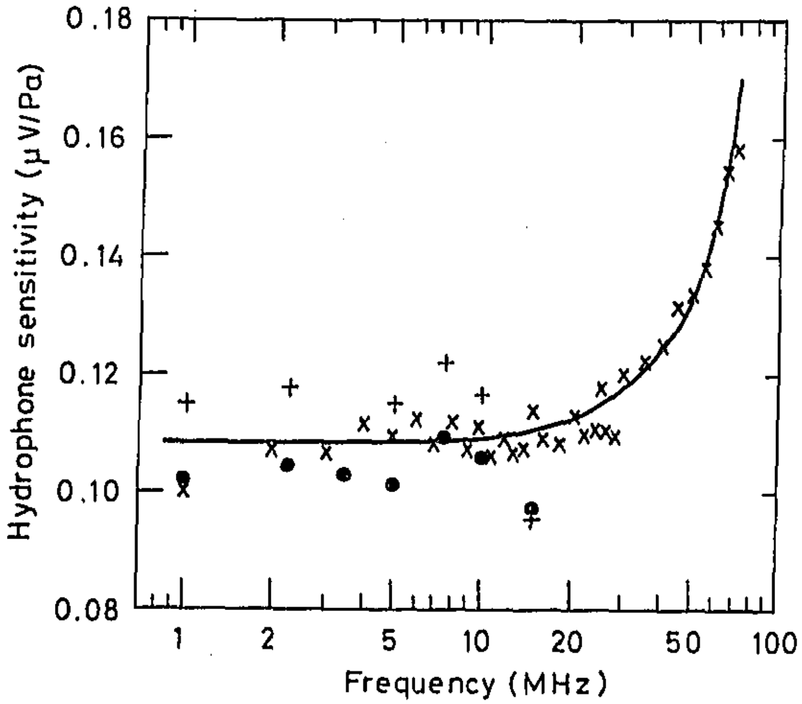

Figure 23 Comparison of the results of three techniques:

x nonlinear propagation technique;

• reciprocity and

+ planar scanning.

The solid line represents Bacon's theoretical frequency response model [78].

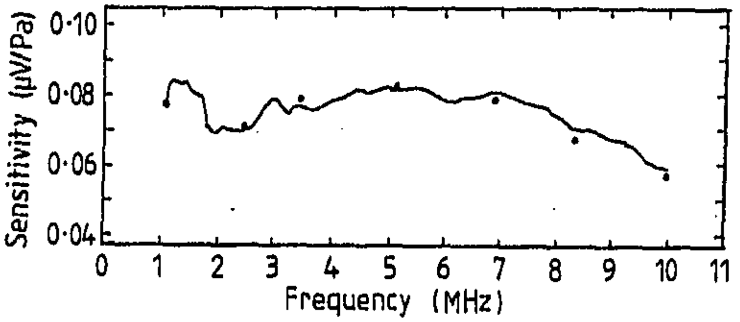

Figure 24 Comparison of reciprocity (line) with planar scanning (points).

Koppelmann et al [34] intercompared two-transducer reciprocity with three-transducer reciprocity over the frequency range 75 to 200 kHz and obtained agreement to within ± 2 dB (± 26%). Nagai et al [71] indirectly intercompared an optical interferometric technique (see Section 2.3) with results obtained from a sphere radiometer (see Section 2.5) because the hydrophone they were using had been calibrated by the manufacturer using the latter technique. Agreement to within ± 10% was achieved with an estimated accuracy of ± 20% on the interferometric technique.

Herman et al [49] intercompared the sphere radiometer technique with planar scanning at 1 MHz and the results agreed within the random uncertainty in the sphere radiometer method of ± 7% (95% confidence limit). The uncertainty in the planar scanning technique is quoted as being greater than ± 5% (the uncertainty in the measurement of total power using a radiation force method).

4.2 Comparison with a standard hydrophone

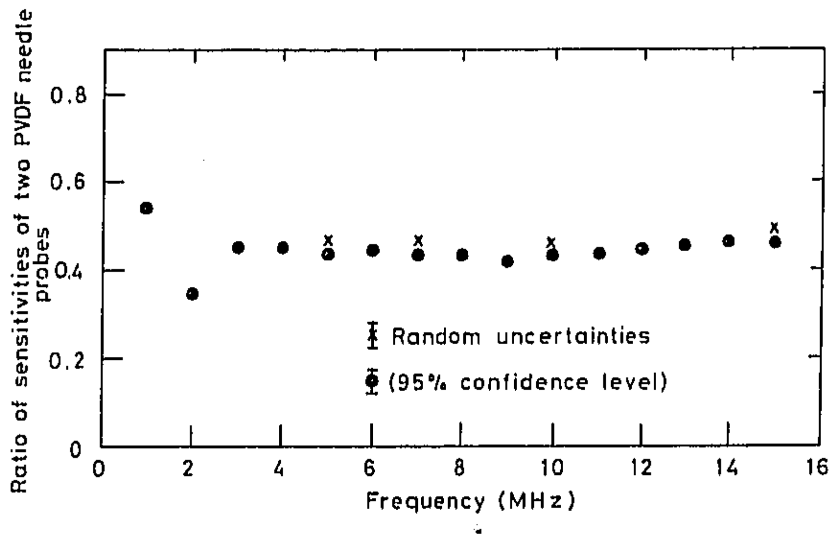

Figure 25 Ratios of the sensitivities of two PVDF needle probe hydrophones from:

x the discrete frequency technique and

• the distorted waveform technique.

An intercomparison between the discrete frequency method of Section 3.1 and the use of a finite-amplitude distorted waveform was undertaken at NPL and is described in Section 3.2. Several different types of membrane hydrophone were calibrated and the results show agreement between the two techniques within the estimated uncertainties (see Figure 21). Two PVDF needle probe hydrophones of the type described by Lewin [6] were calibrated using these two techniques. A graph of these results is presented in Figure 25 and agreement within the estimated uncertainties is shown.

5. SUMMARY

The current state of ultrasonic hydrophone calibration for the characterisation of medical ultrasonic equipment is reviewed and the increasing accuracy of calibrations is evident. Amongst the absolute calibration techniques, optical interferometry has achieved the greatest accuracy, with uncertainties ranging from ± 2.1% at 0.5 MHz to ± 3.5% at 10 MHz and ± 6.3% at 15 MHz reported for the interferometer at NPL. Before this technique was introduced, the reciprocity and planar scanning techniques provided the most accurate calibrations with uncertainties (achieved at NPL) of ± 8% at 1 MHz rising to ± 20% at 15 MHz. Thus, with the introduction of the optical interferometric technique, uncertainties in acoustic intensity measurements arising from the hydrophone calibration have fallen to less than one third of their previous values. For example, at 10 MHz this means a reduction from ± 25% to ± 7%. A calibration using the NPL interferometer also takes less than one tenth of the time required for the planar scanning technique.

Although it should be possible to extend the range of interferometer calibrations up to at least 20 MHz and attempts are being made to extend reciprocity calibrations to higher frequencies, the only viable method of hydrophone calibration currently available above 15 MHz is that using the nonlinear propagation of ultrasound (see Section 2.4). This can provide calibrations up to 100 MHz with an estimated uncertainty of approximately ± 15%. As medical diagnostic equipment produces waveforms containing frequencies of 20 MHz and above, it is obviously essential to develop the ability to calibrate hydrophones at these higher frequencies.

The development of techniques for calibration by comparison with a standard hydrophone (described in Section 3) is important if ultrasonic standards are to be cheaply and reliably disseminated to the medical ultrasound manufacturer and user. There is scope for improvement in both the speed and the accuracy of the current techniques, and this would greatly benefit the progress of medical ultrasound dosimetry.

Two other important stages in the move towards standardisation of the measurement of acoustic field parameters of medical ultrasound equipment are reviewed here. Firstly the development of written standards which give definitions, descriptions and procedures for the calibration and use of ultrasonic hydrophones; secondly, intercomparisons of hydrophone calibration techniques. To date, all reported intercomparisons of absolute techniques have shown general agreement within the attributed uncertainties. However, the same cannot be said for the comparison techniques of Section 3, where more work is required to validate these as suitable methods for disseminating standards.

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