

IEEE Guide for Medical Ultrasound Field Parameter Measurements

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Sponsored by the Subcommittee on Ultrasound in Medicine of the
Standards Activities Committee of the
IEEE Ultrasonics, Ferroelectrics, and Frequency Control Society

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Coordinating
Committees*

IEEE Std 790-1989



Published by the Institute of Electrical and Electronics Engineers, Inc., 345 East 47th Street, New York, NY 10017, USA.

June 29, 1990

SH 13003

IEEE Guide for Medical Ultrasound Field Parameter Measurements

Sponsor

Subcommittee on Ultrasound in Medicine
of the Standards Activities Committee
of the
IEEE Ultrasonics, Ferroelectrics, and
Frequency Control Society

Approved August 10, 1989

IEEE Standards Board

Approved January 12, 1990

American National Standards Institute

Abstract: IEEE Std 790-1989, *IEEE Guide for Medical Ultrasound Field Parameter Measurements* (ANSI), describes procedures for measuring medical ultrasound field parameters such as pressure, power, and intensity. It is intended for use by persons involved in measurement of acoustic fields produced by medical ultrasound instruments.

Keywords: Acoustic field measurement, hydrophone, optics, radiation force, thermal techniques.

Library of Congress Catalog Number 90-083096

ISBN 1-55937-034-3

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(This Foreword is not a part of IEEE Std 790-1989, IEEE Guide for Medical Ultrasound Field Parameter Measurements (ANSI).)

IEEE Standards Publications are of three types—standards, recommended practices, and guides. This document is a guide, in which recommendations are made. It serves as a resource for the reader to assist in selection of measurement procedures and to aid in implementing “cookbook” descriptions for building and using devices that measure medical ultrasound field parameters such as pressure, power, and intensity. It is intended for use by persons involved in measurement of acoustic fields produced by medical ultrasound instruments. A single source describing construction and use of these devices has not previously existed.

Mention of specific products or commercial devices or sources does not imply endorsement by the IEEE or any institutions with which the developers of this guide are affiliated.

William O'Brien's conception of the guide and his initial groundwork are acknowledged. Development of this guide was a project of the Subcommittee on Ultrasonics in Medicine of the Standards Activities Committee of the IEEE Ultrasonics, Ferroelectrics, and Frequency Control Society (UFFCS). The Measurement Guide Working Group, which consisted of the seven editors of this guide, included the following members:

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The original draft of this guide was approved by the IEEE Standards Board on June 9, 1988. Because of delays in production of the guide, minor changes and updates to Chapter 1, Hydrophone, became necessary and were incorporated in May 1989. The final conditions for approval of this guide were met on August 10, 1989. The guide was approved conditionally on June 1, 1989, with the following membership:

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Chapter 1

Hydrophone

1.1 Introduction. This chapter of the guide has been divided into three parts: hydrophone types, calibration and evaluation techniques, and measurement techniques.

The first part contains a description of four types of hydrophones that are or have been commercially available. An attempt has been made to keep the descriptions generic. However, the specifics of each contribution may tend to reflect the author's familiarity with a particular hydrophone, so the descriptions may not apply exactly to all the possible sources. These descriptions are, however, believed to be representative of the hydrophone type. For current information about commercial sources, it may be helpful to contact one or more of the individuals named in the List of Contributors at the beginning of this guide.

All hydrophones described have as their active element the piezoelectric polymer polyvinylidene fluoride (PVDF). This is not meant to imply that suitable broadband hydrophones could not be constructed using other materials, such as quartz or a piezoceramic. In fact, there exist in the literature descriptions of such devices. However, the water-borne ultrasound pulses encountered in medical diagnostic systems can have significant spectral content extending well beyond 20 MHz and, to the knowledge of the developers of this guide, no one has marketed a nonpolymeric hydrophone that would be considered acceptable for measuring such pulses.

The four hydrophone types are all generally useful for characterizing medical ultrasound fields. However, each has specific advantages that may be important to consider in certain applications. For example, the baffled design with its rf shielding and integral preamplifier has the greatest hydrophone sensitivity (defined later) and signal-to-noise ratio; the small size of the needle-like probe makes it well-suited for measurements in continuous wave fields; and, if a very smooth frequency response or a high degree of acoustic transparency is critical, then the membrane design should be considered. An adaptation of the membrane approach, in which the reservoir formed by the polymer film and support structure is filled with an acoustical backing material, results in an improved signal-to-noise ratio, although the transparency property of the membrane design is sacrificed.

Factors such as these, along with price, availability, and possibly mechanical considerations, will determine which hydrophone is best suited to a particular use. However, no matter which hydrophone is chosen, it is often necessary to perform periodic in-house evaluations of calibration and performance. This is particularly true since reliable information is not always available from the hydrophone manufacturer, and also since hydrophone properties may change with time. Therefore, the second part of this chapter outlines methods that have been used for checking hydrophone performance. Sections 1.4.1 and 1.4.2 cover reciprocity and planar scanning techniques for absolute calibration of hydrophones at a single frequency. For the planar scanning technique, a source of known ultrasonic power is needed. One such source developed by the National Institute of Standards and Technology is described in 1.4.3.

Sections 1.4.4 through 1.4.7 contain various approaches for calibrating hydrophones over a range of frequencies via spectral analysis of a broadband acoustic signal; 1.4.4 and 1.4.5 use the nonlinear propagation properties of water. In 1.4.6 a calibration pulse is generated using a thick piezoelectric disk source transducer, and in 1.4.7 time-delay spectrometry (TDS) is introduced for calibration purposes.

TDS also can be used to determine a hydrophone's directional response, as shown in 1.4.7. Sections 1.4.8 and 1.4.9 present two other methods for finding the directivity characteristics of a hydrophone.

The contributions in the last part of this chapter, 1.5, are related to measurements that can be performed using miniature hydrophones. Section 1.5.1 describes a basic scanning system for obtaining beam profiles and hydrophone voltage waveforms. Once these data are recorded, the information contained in 1.5.2 can be used to compute various acoustic pressure and intensity parameters. An automated system for obtaining this information is described in 1.5.3 and, to close out the chapter, a procedure for plotting the phase distribution of an ultrasound beam is presented.

In all of this material an attempt has been made to keep the terminology consistent and the format similar, but otherwise the content reflects the experience and style of the individual contributors. One point that can cause confusion is the term *sensitivity*, which can have various meanings. In general, two separate types of definitions are in use. In one, sensitivity is the ratio of a response to a stimulus; in the other, it is the minimum stimulus that will produce a detectable response. (This latter sensitivity is sometimes referred to as a *minimum detectable level*.) When one speaks of "hydrophone sensitivity," it is usually the first definition that is implied, and typical response/stimulus units are volts per pascal. However, to be useful, the measurement conditions under which this sensitivity was found need to be known; i.e., field conditions, cable length, electrical load, etc. Therefore, over the years a number of modifiers have been attached to the term *sensitivity*, such as *free-field*, *voltage*, *pressure*, *open-circuit*, and *end-of-cable*. These modifiers can have overlapping meanings, so to avoid confusion the following convention for hydrophone sensitivity will be used unless stated otherwise: *The hydrophone sensitivities given in 1.3.1 through 1.3.4 are free-field and end-of-cable, and are open-circuit unless an electrical load is specified.*

In the second and third parts of this chapter (covering calibration, evaluation, and measurement techniques), when sensitivity is specified under the heading "Sensitivity of Technique," it conforms to the second general definition; namely, minimum stimulus to produce a detectable response. For example, in 1.4.1, the reciprocity calibration technique has a sensitivity, or minimum detectable level, of $3 \cdot 10^{-9}$ V/Pa, which can be interpreted to mean that in order for a change in hydrophone free-field, end-of-cable sensitivity to be consistently and reliably measured, that change must be greater than $3 \cdot 10^{-9}$ V/Pa.

Before leaving the topic of sensitivity, a comment should be made about the use of hydrophone measurements to derive intensity parameters. In general, acoustic intensity is found from the product of the particle pressure and the complex conjugate of the particle velocity, both of which can be expressed as analytic signals whose real and imaginary parts form a Hilbert transform pair ([B24]¹ and [B45]). In medical ultrasound fields, sufficient accuracy is obtained by the simpler and more common relationship, $I(t) = p^2(t)/\rho c$, where $I(t)$ is instantaneous intensity, $p(t)$ is instantaneous pressure, and ρ and c are respectively the density and speed of sound for the propagation medium. However, this expression should be used only for free-field plane or spherical waves ([1] and [2]). As such, it is generally considered to be valid only in the far field or at the focus of a source transducer. If the "intensity response factor" K_f^2 , having units of $V^2 W^{-1} cm^2$, is used to compute an intensity (see 1.4.2 and 1.5.2), then that intensity should be reported as a *derived* rather than as a *measured* value, the propagation medium should be specified, and the assumption of plane or spherical waves should be stated and justified. This same point holds if values for AIUM/NEMA's "pulse intensity integral" [2] are quoted. If no field conditions are specified, then IEC's more general "pulse pressure squared integral" [1] should be used instead.

Another area that can be perplexing is the interpretation and use of directivity specifications. In the descriptions of hydrophone types (1.3.1–1.3.4), directivity data are included under either hydrophone sensitivity, since sensitivity is direction-dependent, or under spatial resolution,

¹The numbers in brackets correspond to those of the references in 1.2; when preceded by B, they correspond to the bibliography in 1.6.

since directional behavior is a function of the size of the active element. When dimensions (i.e., hydrophone effective radius), angles, or frequencies are quoted, they are related by the classical directional function $D(\theta)$ for circular apertures,

$$D(\theta) = 2J_1(x)/x \quad (\text{Eq 1})$$

where

$$x = 2\pi a \sin \theta / \lambda \quad (\text{Eq 2})$$

a is the hydrophone effective radius, θ is the incidence angle of the ultrasonic wave, with $\theta = 0^\circ$ being normal incidence, λ is the acoustic wavelength, and J_1 is a Bessel function of the first kind, of order one. $D(\theta)$ is usually measured at the -3 dB or -6 dB points, at which $x = 1.62$ or 2.22 , respectively ([1] and [2]). Thus, with θ , λ , and x known, Eq 2 can be used to find the radius a . (It should be noted that the hydrophone "effective radius," found from acoustic measurements, may differ from its "geometrical radius," based on physical measurements; see definitions in [1]. When the two differ the effective radius is usually larger.)

Finding the hydrophone effective radius is straightforward; making use of the information is less so. It has often been stated that obtaining an ultrasonic hydrophone having active dimensions small compared to an acoustic wavelength is not practical at megahertz frequencies. Therefore, one must choose the dimensions carefully to minimize the effects of spatial averaging of the pressure wave across the hydrophone's active surface. Guidelines have been provided for this choice by AIUM/NEMA and the IEC. Of these two, the more conservative IEC guideline may be the better choice [B17]. Under this guideline the hydrophone effective radius is chosen as follows:

$$a_h < \lambda z / 4d_s \quad \text{when } z/d_s \geq 1 \quad (\text{Eq 3a})$$

$$a_h < \lambda / 4 \quad \text{when } z/d_s < 1 \quad (\text{Eq 3b})$$

where a_h is the hydrophone effective radius, d_s is the source effective *diameter* (or greatest dimension), λ is the acoustic wavelength, and z is the source-to-hydrophone distance.

As an example, consider a 3.5 MHz, 1 cm diameter imaging transducer with a focal length of 4 cm. Here $a_h < 0.43$ mm, which is within the roughly 0.10–0.75 mm radius range of currently available hydrophones. However, in applications calling for higher frequencies or smaller z/d_s ratios (such as peripheral vessel, small parts, or ophthalmic diagnostic systems), the inequality of Eq 3 rapidly becomes unsatisfiable. Also, the guideline as it stands considers only the fundamental frequency component. If the amplitude of the pressure pulse results in significant finite amplitude distortion, then the requirement would be more demanding than that given by Eq 3.

More work needs to be done on both the effects of spatial averaging and the development of compensating correction factors. In the meantime, it is important that hydrophone users document the hydrophone and field characteristics related to spatial averaging when reporting measurement results.

A picture of a hydrophone voltage waveform showing finite amplitude distortion is given in 1.5.2. This distortion is a common characteristic of high-amplitude pressure waveforms, and it is especially prevalent in focused ultrasonic fields. The peaked and rounded half-cycles correspond to the compressional and rarefactional portions of the wave, respectively. Such waveforms may have frequency components that cause resonance effects in the hydrophone cable ([B5] and [B43]). To reduce this transmission line behavior, the cable must be terminated in its characteristic impedance. This in turn necessitates placing a preamplifier between the hydrophone and cable to drive the low-impedance line. The preamp must of course have flat amplitude and linear phase characteristics, as well as adequate dynamic range, so that it does not introduce distortion into the detected voltage pulse ([B33] and [B21]).

With regard to the recording of hydrophone voltage waveforms in the presence of finite amplitude distortion, the 1981 version of the AIUM/NEMA standard [2] states that a "first or higher order low pass filter with cutoff frequency higher than two times the center frequency of the source transducer may be utilized in the hydrophone signal processing." However, if proper preamplification and cable termination are used, then such filtering is of doubtful value,

because it could lead to significant distortion of the waveform. For hydrophones that do not incorporate the preamp/termination feature, some type of low-pass filtering may be appropriate to reduce the effects of cable resonance. A 20 MHz low-pass cutoff frequency is sufficient to attenuate the cable resonance, but a lower value could distort significantly the measured pressure wave.

Finally, the March 1988 issue of the *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. UFFC-35, was devoted to the subject of ultrasonic exposimetry, and should be consulted for additional information on hydrophone calibration and measurement.

1.2 References. This guide shall be used in conjunction with the following publications.

[1] IEC 87 Central Office 6, 1988, Measurement and Characterisation of Ultrasonic Fields Using Hydrophones in the Frequency Range of 0.5 MHz to 15 MHz.²

[2] Safety Standard for Diagnostic Ultrasound Equipment, *Journal of Ultrasound in Medicine*, suppl. to vol. 2, no. 4, 1983.

1.3 Part I—Hydrophone Types

1.3.1 PVDF Needle-Like Hydrophone

1.3.1.1 Ultrasonic Field Parameter Measured. Acoustic pressure.

1.3.1.2 Phenomenon Involved. Piezoelectricity.

1.3.1.3 Ultrasonic Frequency Range Over Which the Device Is Useful. Useful from 0.1 MHz to >40 MHz. Currently available range of absolute calibration: 0.2 MHz to 15 MHz.

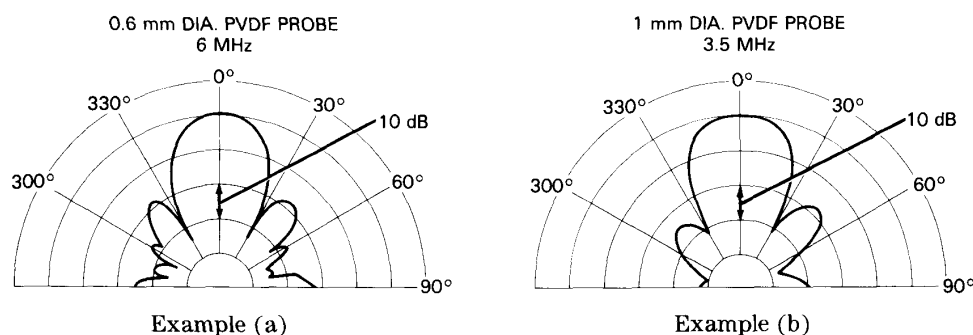
1.3.1.4 Ultrasonic Field Configuration for Which the Device Is Useful. Plane and focused fields (CW and pulsed).

1.3.1.5 Temporal Resolution. Replicates acoustic waveform. Resolution ranges from 10–30 ns and depends on bandwidth of hydrophone and waveform recording device used. The hydrophone responds to instantaneous pressure over useful frequency.

1.3.1.6 Spatial Resolution. Depends on the effective diameter of the probe. For needle-like probes similar to those described by Lewin in [B32], the effective diameter (measured in accordance with [2]), is usually the same as the probe's physical diameter. The smallest needle-like probes available have diameters of the order of 0.5 mm, and they can have directivity patterns that are in excellent agreement with the theory for piston directivity (the classical aperture theory) [B44]. Two examples of directivity patterns are given in Fig 1.

Fig 1

Examples of Directivity Patterns for the Needle-Type Hydrophones Described in Lewin [B32]



For comparison with other PVDF polymer probe designs, see [B43].

²IEC publications are available from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018.

1.3.1.7 Range Over Which the Acoustic Pressure Is Measured. For a signal-to-noise ratio of 20 dB and a bandwidth of approximately 20 MHz, instantaneous pressure amplitudes from approximately 1 kPa to 100 MPa can be measured. This corresponds to instantaneous (plane wave) intensities of about 0.1 mW/cm² to 0.5 MW/cm².

NOTE: The dynamic range depends on the minimum detectable level of the sensor element itself and associated electronics. A thorough discussion of this issue can be found in [B33].

Much lower pressure amplitudes can be measured if a narrowband system is employed. For instance, at least one commercial spectrum analyzer provides a bandwidth as low as 1 Hz. Such narrow bandwidth facilitates intensity measurements on the order of 100 nW/cm².

The maximum acoustic pressure measured with the hydrophone probes has been on the order of 150 MPa. Such high instantaneous pressure amplitudes are encountered in the focal zone of lithotripter devices (i.e., shock-wave kidney stone disintegrators). Linearity of one type of needle-like PVDF probe was recently verified in the interval of instantaneous pressure amplitudes ranging from approximately 1.5 kPa to 150 MPa [B29].

1.3.1.8 Hydrophone Sensitivity. Depends on active area of the sensor element [B33]. For a needle-like probe with a 1 m cable connected to an electrical load of 1 MΩ in parallel with 30 pF, typical sensitivities are as follows: 1 mm effective diameter: -260 dB re 1 V/μPa, or $\approx 10^{-7}$ V/Pa; 0.6 mm effective diameter: -270 dB re 1 V/μPa, or $\approx 3 \cdot 10^{-8}$ V/Pa.

Figure 2 shows examples of absolute end-of-cable voltage sensitivities of two needle-like PVDF hydrophones in water, obtained using two-transducer reciprocity calibration ([B10] and [B16]) combined with the TDS technique ([B30] and [B12]).

1.3.1.9 Reproducibility. $\pm 2\%$ (± 0.2 dB) over pressure range, without repositioning of hydrophone.

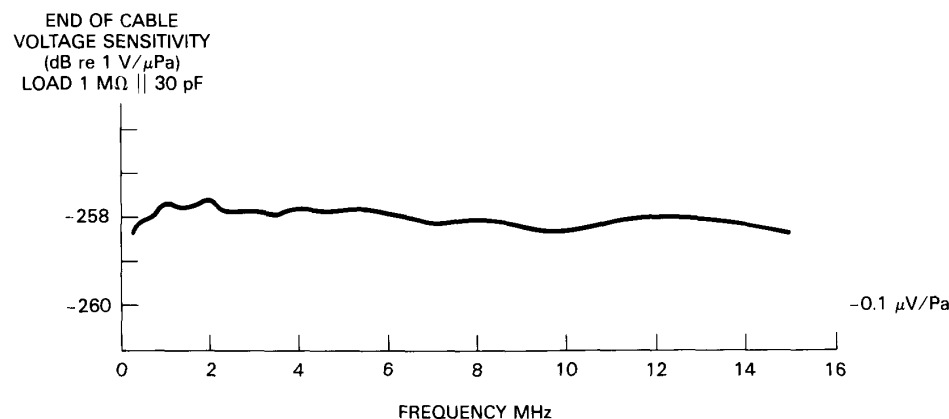
The overall uncertainty of the absolute calibration depends on the frequency range. Typical values are as follows: ± 0.8 dB (0.5–10 MHz); ± 1.5 –2 dB (10–20 MHz). See also [B10] and [B16].

1.3.1.10 Construction Details. See [B32] for an example.

1.3.1.11 Electronic Details. Excellent immunity to radio-frequency (rf) interference is provided by enclosing hydrophone in rf shield.

1.3.1.12 Procedure for Performing Measurements. A water tank (preferably with distilled and degassed water) and recording device calibrated in absolute volts, such as a good quality oscilloscope, are required. The acoustic pressure p is calculated from the relationship $p = V/M$,

Fig 2
Example of End-of-Cable (1 m) Sensitivity for the 1 mm
Diameter Needle-Type Hydrophone Described in Lewin [B32]



The terminating load is 1 MΩ || 30 pF, a typical input impedance for an oscilloscope or spectrum analyzer.

where V is the amplitude of the signal in volts and M is the end-of-cable sensitivity of the hydrophone in V/Pa, as read from the calibration chart. Note that M is specified for a given termination (i.e., 1 M Ω in parallel with 30 pF). Also note that the alignment of the hydrophone and acoustic source is critical.

The water should be degassed to prevent a thin air film or microbubbles from adhering to the sensitive element of the needle-like hydrophone (and other types as well). Placing commercially available hollow plastic spheres or plastic film on the water surface is one of the precautions that may be used to minimize air penetration into the water. Another is to periodically rinse the hydrophone with degassed water. The use of a detergent wetting agent directly on the hydrophone is in general not recommended due to the relatively fragile construction of the probes.

For procedures to determine the origin of the possible distortions observed in the recorded pressure-time waveforms, consult [B33]. Also see [1], [2], and [B12].

1.3.2 PVDF Baffled Hydrophone

1.3.2.1 Ultrasonic Field Parameter Measured. Acoustic pressure.

1.3.2.2 Phenomenon Involved. Piezoelectricity.

1.3.2.3 Ultrasonic Frequency Range Over Which the Device Is Useful. Calibrated from 1 MHz to 10 MHz; useful from 0.5 MHz to 20 MHz.

1.3.2.4 Ultrasonic Field Configuration for Which the Device Is Useful. Plane wave or focused beam; any time waveform, for example, a single cycle of rf.

1.3.2.5 Temporal Resolution. Replicates acoustic waveform; spurious responses are more than 30 dB below main signal.

1.3.2.6 Spatial Resolution. Averages acoustic pressure over 0.5–1.5 mm diameter of PVDF detecting element.

Acceptance angle (full width at half maximum) agrees with classical aperture theory. For example, at 3.5 MHz the acceptance angle is 23 degrees for the 1.5 mm diameter element.

1.3.2.7 Range Over Which the Acoustic Pressure Is Measured. The acoustic pressure can be as small as 2 kPa (peak-to-peak), corresponding to a temporal average intensity of 34 $\mu\text{W}/\text{cm}^2$, for a signal-to-noise ratio of 20 dB and a bandwidth of 10 MHz.

NOTE: Smaller acoustic pressures can be measured if the bandwidth of the receiver (such as a spectrum analyzer) is set narrower than 10 MHz. For example, at a 1 kHz bandwidth and a signal-to-noise ratio of 20 dB, the temporal average intensity can be as small as 3.4 nW/cm². The noise originates from thermal noise in the piezoelectric element and noise of the built-in preamp.

The maximum acoustic pressure that can be measured is 95 MPa (peak-to-peak), corresponding to a temporal average intensity of 76 kW/cm². The maximum signal is limited by saturation of the preamplifier.

The hydrophone is capable of a dynamic range of over 93 dB.

1.3.2.8 Hydrophone Sensitivity. End-of-cable sensitivity for a 1.5 mm diameter element is typically -254 dB with respect to 1 V/ μPa , or $2 \cdot 10^{-7}$ V/Pa, for a 50 Ω load termination.

1.3.2.9 Reproducibility. $\pm 2\%$ (± 0.2 dB) over pressure range, without hydrophone repositioning.

1.3.2.10 Construction Details. The following design features are possible using the baffled element configuration:

- (1) Active element (30 μm thick PVDF) can be totally enclosed in a metal housing, thus greatly reducing electromagnetic interference from radio and/or TV transmitters.
- (2) Hydrophone can be immersed underwater indefinitely since the active element never touches the water.
- (3) Hydrophone can be filled with oil to prevent acoustic reflections from trapped air.
- (4) Hydrophone can be filled with acoustic absorbing material to prevent unwanted acoustic reflections within the housing.
- (5) PVDF disk can be held in place by mechanical pressure; no solder or epoxy bonds are made to the PVDF disc.
- (6) Front edge of housing can be covered with acoustic material to reduce acoustic diffraction from the hydrophone itself.

1.3.2.11 Electronic Details

- (1) Hydrophone has a built-in preamp with gain of unity to convert the high PVDF electrical impedance to less than 10 Ω output impedance.

- (2) DC power supply for preamp of typically 15–30 V, 250 mA, must accompany the hydrophone.
- (3) A cable of any length can connect the hydrophone to the oscilloscope without reducing the voltage level, changing the hydrophone sensitivity, or degrading the signal-to-noise ratio.
- (4) For accurate calibration, the end of the (50 Ω) cable should be terminated in a 50 Ω resistance at the oscilloscope (or auxiliary amplifier if one is used).

1.3.2.12 Procedure for Performing Measurements. *Precautions and suggestions:*

- (1) Oscilloscope must be calibrated in absolute volts; the accuracy of the reading from the oscilloscope limits the accuracy of the acoustic measurement.
- (2) Alignment of the hydrophone relative to the source transducer is critical in obtaining an accurate measurement (especially at high frequencies, ≈ 10 MHz). A good technique is to manually rock the hydrophone back and forth to maximize the output signal. Then mechanically lock hydrophone in that position.
- (3) A mechanical drive system (perhaps computer controlled) is extremely useful for mapping field patterns.
- (4) With high-power acoustic waves, especially for focused transducers, nonlinear effects in the water can easily produce nonsinusoidal waveforms. Based on electrical tests of the built-in preamp, the output of the hydrophone has little distortion until the output is 19 V peak-to-peak. Acoustic nonlinearities in the water occur at much lower output levels. However, in a nonlinear field the preamp slew rate can limit the effective dynamic range. This effect is important for acoustic pressures above 10 MPa [B21].

Also see [B46], [B47], and [B43].

1.3.3 PVDF Membrane Hydrophone—Single Active Element. Three types of membrane hydrophones having single active elements are available, as shown in Fig 3: coplanar shielded, bilaminar, and differential output. The choice depends on the application (see Table 1).

1.3.3.1 Ultrasonic Field Parameter Being Measured. Acoustic pressure, once the hydrophone has been calibrated. Under conditions of plane progressive waves, intensity may be derived.

1.3.3.2 Phenomenon Involved. Piezoelectricity.

1.3.3.3 Ultrasonic Frequency Range Over Which the Device Is Useful. 500 kHz to 40 MHz. (100 MHz for devices with membranes of thickness 0.009 mm.)

1.3.3.4 Ultrasonic Field Configuration for Which the Device Is Useful. In pulsed fields, all three types may be used.

Table 1
A Guide to the Choice of the Most Appropriate Membrane Hydrophone
for Different Environmental Conditions and Types of Ultrasonic Fields

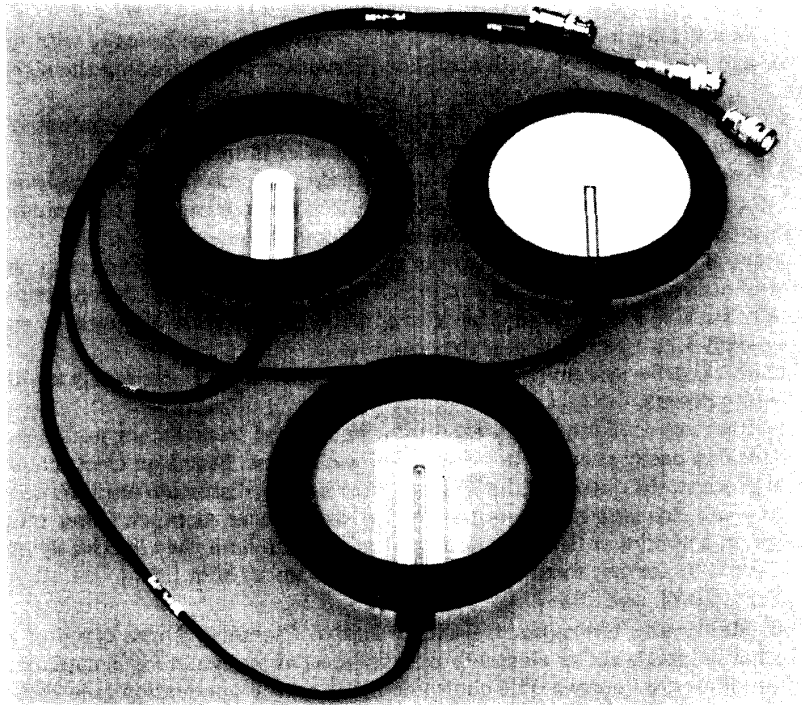
	Coplanar Shielded	Bilaminar	Differential Output
Environment			
Deionized water	***	***	***
Tap water	*	***	*
Electrically noisy	**	***	***
Transducer field			
Pulsed	***	***	***
CW			
Hydrophone not rotated	**	*	**
		for above 2 MHz	
Hydrophone rotated to prevent standing waves	**	***	***

*Not acceptable.

**Poor.

***Good.

NOTE: This table assumes the membrane hydrophones are made from PVDF film of thickness 0.025 mm.



(1) Top left — coplanar shielded; (2) Top right — bilaminar; (3) Bottom — differential output

Fig 3
Examples of Three Types of Membrane Hydrophones

In continuous wave fields, bilaminar or differential output types may be used to overcome electrical interference effects. The hydrophone should be rotated until any observed acoustic interference effects are decreased to an acceptable level. The angle of rotation, θ , generally is equal to that calculated using geometrical acoustics, in which a ray from the center of the source transducer is reflected from the membrane so as to miss the opposite edge of the source. That is, $\theta = 0.5 \tan^{-1}(a/x)$, where a is the source radius and x is the distance between the source and the hydrophone. Once this angle is determined, a correction for the directional response of the hydrophone should be made.

For example, if a membrane hydrophone having a 0.5 mm diameter active element is placed 20 mm from a 20 mm diameter, 1.5 MHz physiotherapy transducer, then the hydrophone must be rotated 13 degrees. The directivity correction would then be +6% for acoustic pressure parameters and +12% for intensity parameters. Directivity corrections may be obtained from separate measurements (see 1.4.8 and 1.4.9) or from published data (e.g., see [B41]).

In focused fields, any type may be used provided the active element is sufficiently small.

1.3.3.5 Temporal Resolution. 20 ns.

1.3.3.6 Spatial Resolution. Dependent on the effective size of the active element in the particular ultrasonic field. Hydrophones with geometrical diameters of the active element of 0.1, 0.2, 0.5, and 1 mm have been produced.

1.3.3.7 Range Over Which the Acoustic Pressure Is Measured. For a 1 mm active element hydrophone, from 300 Pa to 100 MPa have been measured.

1.3.3.8 Hydrophone Sensitivity. Typically, for a 1 mm active element hydrophone having a film thickness of 25 μm , the open-circuit, end-of-cable sensitivity is 10^{-7} V/Pa at 1 MHz and

varies by less than 10% in the frequency range of 0.5 MHz to 15 MHz. For a 1 mm active element hydrophone, the minimum detectable acoustic pressure (equivalent to the noise) in a 10 MHz bandwidth is 300 Pa for a coplanar device, and 100 Pa for a bilaminar or differential output device.

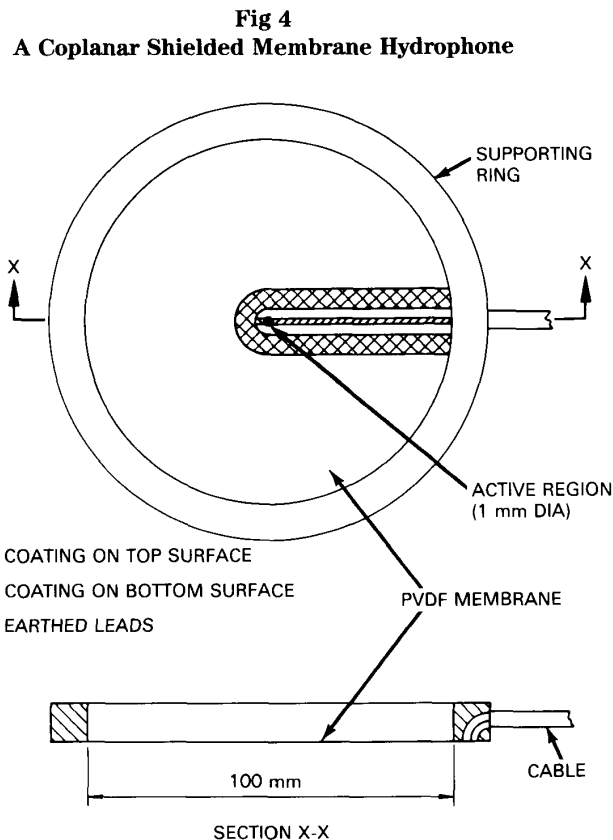
The sensitivity of all types of hydrophones depends on the direction of incidence of the ultrasound and is maximum when the ultrasound is incident normal to the plane of the membrane. For a hydrophone with an active element diameter of 1 mm, the full width at the -6 dB points in the directional response function is typically 68°, 24°, and 11° at 1 MHz, 5 MHz, and 10 MHz, respectively.

The temperature dependence of membrane hydrophone sensitivities in the temperature range of 15 °C to 25 °C is given below for different types of devices.

Type	Variation of Sensitivity (% per °C)	
	2 MHz	10 MHz
All coplanar shielded	0.6	0.6
0.5 mm bilaminar	0.1	0.4
1 mm bilaminar	0.0	0.2

1.3.3.9 Reproducibility. $\pm 2\%$ (standard error of the mean) over pressure measurement range, without repositioning of hydrophone.

1.3.3.10 Construction Details. Figure 4 shows a schematic diagram of a coplanar shielded hydrophone.



Items constructed: Water test tank, hydrophone support, transducer support, and scanning facilities.

See Figs 5 and 6 for typical configurations.

1.3.3.11 Electronic Details. The hydrophone is connected to a signal measurement system either directly or through an amplifier with high input impedance. A differential amplifier is essential for the differential output type of hydrophone. A correction must be made for the change in sensitivity of a hydrophone when connected to an electrical load if the impedance of this load differs from that quoted in the statement of sensitivity. Since the hydrophone is a source of electrical charge, the change in sensitivity may be determined from knowledge of the additional capacitive load and the capacitance of a membrane hydrophone, which is typically 100 pF in water. Although a more general analysis is given in [1], the end-of-cable sensitivity, M_L , is given in terms of the end-of-cable open-circuit sensitivity, M_C , by

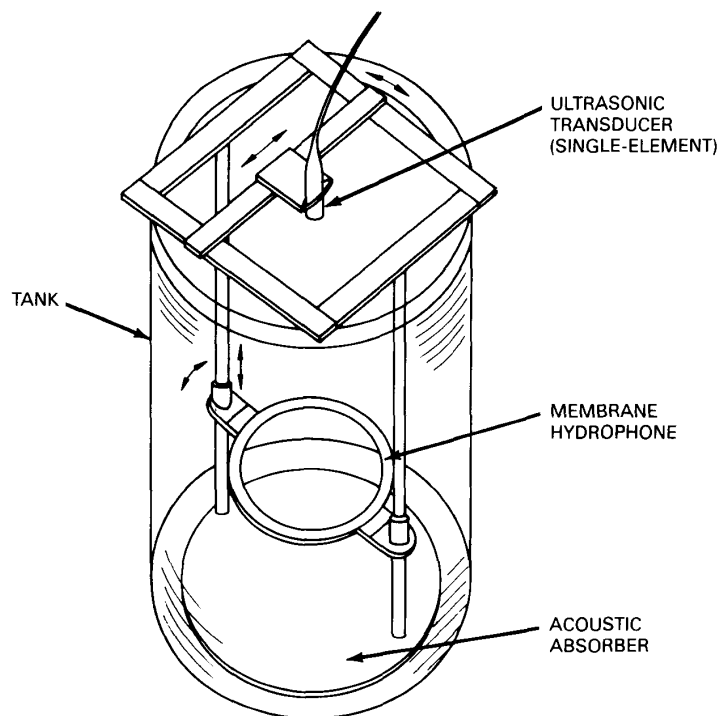
$$M_L = M_C [C/(C + C_L)] \quad (\text{Eq 4})$$

where C is the capacitance of the hydrophone and C_L is the capacitance of the load (input capacitance of an oscilloscope, for example).

1.3.3.12 Procedure for Performing Measurements

- (1) Choose the most appropriate type of membrane hydrophone (Table 1) and one with a suitable size of active element for the particular ultrasonic field to be characterized.
- (2) Mount in a test tank—see, for example, Figs 5 and 6.
- (3) Connect the hydrophone to a measurement system, such as an oscilloscope.
- (4) For pulsed systems, provide a trigger to the oscilloscope.

Fig 5
A Typical Test-Tank Configuration in Which the Source Transducer Face Is Immersed in Water and the Hydrophone Is Horizontal



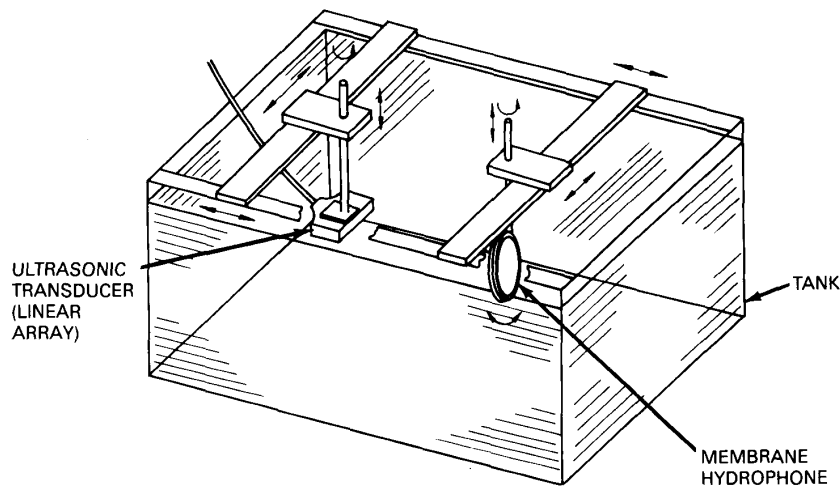


Fig 6
A Typical Test-Tank Configuration in Which the Source Transducer and Hydrophone Are Fully Immersed in Water

- (5) Move the hydrophone to the desired position in the field and display the received signal waveform. Optimize the tilt and rotation of the hydrophone about its active element in order to maximize the received signal.
- (6) Measure the signal voltage level, U , at the point of interest in the waveform. Convert to acoustic pressure, p , using the equation

$$p = U/M \quad (\text{Eq 5})$$

where M is the end-of-cable sensitivity of the hydrophone for an electrical load given by the oscilloscope's input impedance. Note that this equation relates to p and U at the particular point on the temporal waveform.

NOTE: The manufacturers' recommendations should be followed at all times to ensure long lifetime of membrane hydrophones (many years).

Also see [B37].

1.3.4 PVDF Membrane Hydrophone with Filled Reservoir

1.3.4.1 Ultrasonic Field Parameter Measured. Acoustic pressure.

1.3.4.2 Phenomenon Involved. Piezoelectricity.

1.3.4.3 Ultrasonic Frequency Range Over Which the Device Is Useful. 0.5 MHz to 40 MHz.

1.3.4.4 Ultrasonic Field Configuration for Which the Device Is Useful. Pulsed plane wave and focused fields.

1.3.4.5 Temporal Resolution. Responds to instantaneous pressure over useful frequency range.

1.3.4.6 Spatial Resolution. The effective radius, measured in accordance with [2], is 0.4 mm at 2.5 MHz. The geometrical radius is approximately 0.25 mm.

1.3.4.7 Range Over Which the Acoustic Pressure Is Measured. > 300 Pa. Hydrophone rms noise level for 20 MHz bandwidth is < 30 μV , which corresponds to < 300 Pa rms noise pressure level over this band. The upper limit is not known, but it is at least 5 MPa.

1.3.4.8 Hydrophone Sensitivity. Depends on the type of piezoelectric film used. Open-circuit, end-of-cable sensitivities are usually between -260 and -270 dB re 1 V/ μPa (10^{-7} - $3 \cdot 10^{-8}$ V/Pa) from 1-10 MHz, and over this range sensitivity variations of within ± 1 dB are achievable. The sensitivity is independent of the ultrasound propagation medium.

1.3.4.9 Reproducibility. $\pm 2\%$, without hydrophone repositioning.

1.3.4.10 Construction Details. The probe is a circular membrane design, typically several centimeters in outside diameter, acoustically backed, and housed in a cylindrical metal can 2–3 cm deep. This hydrophone differs from the conventional membrane designs in that the reservoir formed by the membrane and metal housing is filled with a rubber material having a low dielectric constant and an acoustic impedance close to that of water. Also, the entire outer surface of the hydrophone housing is electrically shielded.

1.3.4.11 Electronic Details. A preamplifier can be located on the back of the metal cylinder.

1.3.4.12 Procedure for Performing Measurements

- (1) Place hydrophone in measurement tank and position at desired location in pulsed ultrasonic beam.
- (2) Observe waveform on oscilloscope.
- (3) Compute acoustic pressure using hydrophone end-of-cable sensitivity.

1.4 Part II—Calibration and Evaluation Techniques

1.4.1 Two-Transducer Reciprocity Calibration of Hydrophones

1.4.1.1 Hydrophone Parameter Measured. End-of-cable sensitivity (hydrophone voltage response to acoustic pressure).

1.4.1.2 Phenomenon Involved. Self-reciprocity of an auxiliary transducer.

1.4.1.3 Ultrasonic Frequency Range Over Which the Technique Is Applicable. 0.5 MHz to 15 MHz.

1.4.1.4 Ultrasonic Field Region for Which the Technique Is Applicable

$Z > 0.8N$ (optimal region, $1.5N - 3N$)

Z = distance from the auxiliary transducer

$N = a^2/\lambda$ = Near-field length

a = radius of the auxiliary transducer

λ = acoustic wavelength

1.4.1.5 Temporal Resolution. As expressed by the upper frequency limit.

1.4.1.6 Spatial Resolution. Depends on the hydrophone diameter.

1.4.1.7 Range Over Which the Hydrophone Sensitivity Is Measured. $> 3 \cdot 10^{-8}$ V/Pa.

1.4.1.8 Sensitivity of Technique. $3 \cdot 10^{-9}$ V/Pa.

1.4.1.9 Accuracy of Technique. $\pm 10\%$.

1.4.1.10 Construction Details

- (1) *Items purchased:* Alignment facilities for auxiliary transducer and hydrophone (optical adjustment instrumentation).
- (2) *Items constructed:* Water tank having dimensions about $0.6 \text{ m} \times 0.4 \text{ m} \times 0.4 \text{ m}$; reflector and reflector alignment; and water degassing facility.

See Fig 7 for a schematic of the calibration arrangement.

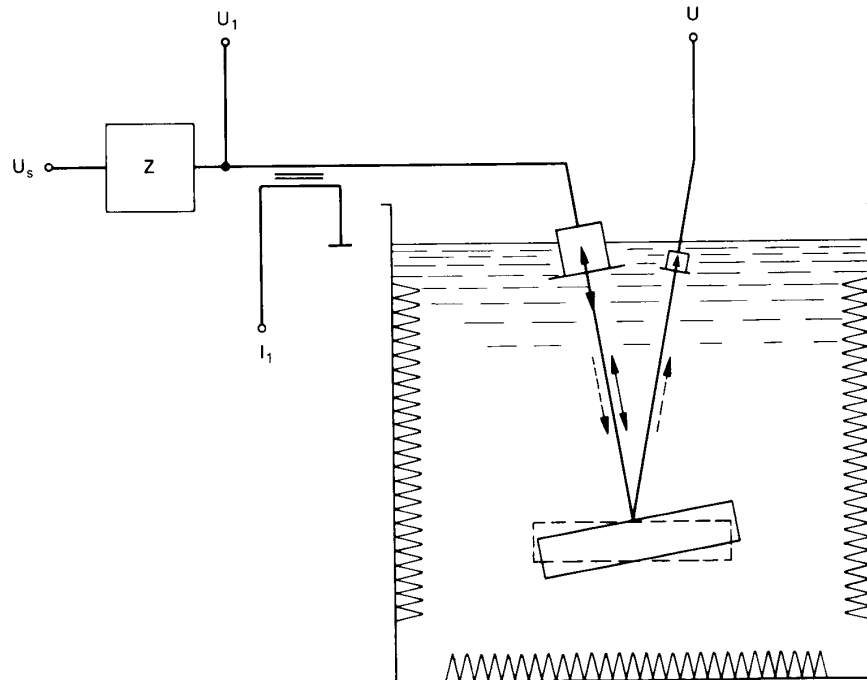
1.4.1.11 Electronic Details. *Items needed:*

- (1) Set of broadband transducers
- (2) Tone-burst generator
- (3) Precision attenuator (0.1 dB) and termination
- (4) Current probe
- (5) Coaxial switch
- (6) Oscilloscope
- (7) Spectrum analyzer (for precision measurements)
- (8) Preamplifier

See Fig 8 for a block diagram of the electronic equipment.

1.4.1.12 Procedure for Performing Measurements

- (1) Measuring tank is filled with degassed, distilled water.
- (2) Components are stored in water for at least 1 h.
- (3) Auxiliary transducer is aligned with respect to the reflector.
- (4) Self-reciprocity calibration of the auxiliary transducer is obtained.
- (5) Reflector is turned so as to center the reflected ultrasonic beam on the hydrophone.



where

- U_s = the output voltage from the tone-burst generator
- Z = a matching network
- U_1 and I_1 = the reciprocal auxiliary transducer's voltage and current, respectively
- U = the hydrophone voltage

Fig 7
Schematic of the Calibration Arrangement

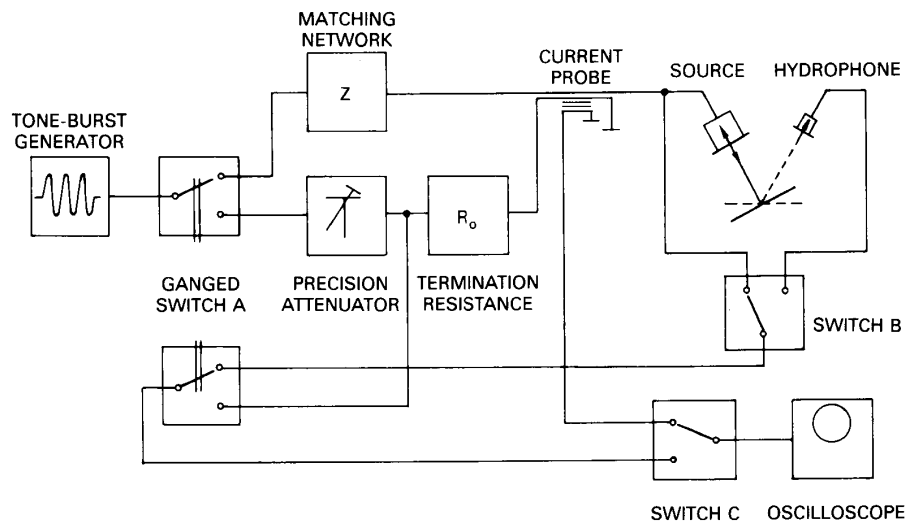


Fig 8
Block Diagram of the Electronic Equipment

- (6) Hydrophone output voltage and transmitting current of auxiliary transducer are measured.
- (7) Final result is calculated according to equations given in the literature; e.g., see [B10].

NOTE: For continuous waves, the two-transducer reciprocity calibration using time-delay spectrometry is applied. See [B34].

Also see [B9], [B16], [B26], and [B28].

1.4.2 End-of-Cable Sensitivity Calibration of a Miniature Hydrophone by Scanning a Transducer Assembly Beam of Known Power and Frequency

1.4.2.1 Hydrophone Parameter Measured. End-of-cable sensitivity. The acoustic pressure is detected by a hydrophone at a point in the field of a “source” transducer whose output power, W , previously has been determined for a specified frequency. The axial location of the measurement is the point where the hydrophone response is maximized. This distance usually occurs near the focal plane for focused transducer assemblies or near the transition distance for nonfocused assemblies. For either case, the assumption of phase coherence (i.e., plane waves) can be made, and acoustic intensity may be derived.

1.4.2.2 Phenomenon Involved. Conversion of the mechanical force of incident plane waves of a given frequency into a voltage response of the hydrophone. The end-of-cable sensitivity for the hydrophone is given by the factor M in V/Pa. Since a condition of plane wave propagation exists, a hydrophone intensity response factor at frequency f , K_f^2 , can be expressed as

$$K_f^2 = 10^4 \rho c M^2 \quad \text{V}^2 \text{W}^{-1} \text{cm}^2 \quad (\text{Eq 6})$$

where ρ is the physical mass density (kg/m^3), and c is the speed of sound in the medium (m/s) (usually pure water).

1.4.2.3 Ultrasonic Frequency Range Over Which the Technique Is Applicable. Essentially over the range of frequencies available from source transducers that previously have had their power outputs determined. For diagnostic purposes, about 1–15 MHz.

1.4.2.4 Ultrasonic Field Configuration for Which the Technique Is Applicable. Along central axis (not necessarily geometric axis) of the transmitting source transducer beam where the received hydrophone response is both maximized and an assumption of plane wave propagation is valid. (As pointed out earlier, these conditions are essentially met near the focal plane for focused transducer assemblies or at the transition distance for nonfocused assemblies.)

1.4.2.5 Temporal Resolution. Depends on ability of hydrophone and display unit (usually a dual-channel, time-delayed oscilloscope) to resolve transmitted tone-burst pulses of from 15 to 20 cycles and pulse durations as low as $0.5 \mu\text{s}$. This translates into a minimum frequency bandwidth of about 40 MHz.

1.4.2.6 Spatial Resolution. Technique requires integration under orthogonal lateral response profiles taken by hydrophone. To avoid the need for deconvolution or other procedures to correct for spatial averaging because of the size of the hydrophone element, the diameter of the hydrophone should be less than or equal to $0.5\lambda L/D$, where λ is the wavelength of the incoming tone-burst pulses, L is the axial distance at which profiles are taken, and D is the diameter of the transmitting source transducer. For unfocused source transducers, as long as L is greater than the near-to-far field transition distance, a 1 mm diameter hydrophone is usually sufficient.

1.4.2.7 Range Over Which the Sensitivity Calibration Can Be Obtained. $> 10^{-8}$ V/Pa.

1.4.2.8 Uncertainty of Technique. The uncertainty in the intensity response factor determined by this scanning procedure has been shown to be about $\pm 20\%$ for polymer (PVDF) hydrophones. For ceramic (PZT) hydrophones this value may be as high as 300% due to local anomalies.

1.4.2.9 Construction Details

- (1) *Items purchased:* Radiation conductance (ratio of acoustic power emitted to square of rms excitation voltage) measurements performed by The National Institute for Standards and Technology (NIST) on a minimum of three source transducers. These may be NIST-type transducers (see 1.4.3 in this chapter and [B14]), or broadband, focused

transducer assemblies used in diagnostic ultrasound examinations. Recommended center frequencies are 2.25 MHz, 3.5 MHz, and 7.5 MHz.

- (2) *Items constructed:* Scanning assembly and hydrophone and transducer mount as described in [2], Sections 3.3.2.1 and 3.3.2.2. [Assume existence of miniature hydrophone to be calibrated (preferably the PVDF type).]

1.4.2.10 Electronic Details. *Items needed:*

- (1) Tone-burst generator (variable amplitude output)
- (2) Frequency counter
- (3) Oscilloscope

1.4.2.11 Procedure for Performing Measurements

- (1) Mount NIST-calibrated source transducer and hydrophone to be calibrated in scanning assembly.
- (2) Select appropriate tone-burst frequency, f , and excitation voltage level for which radiation conductance value has been determined. ($V_{p-p} \leq 4-5$ V so as not to damage transducer.)
- (3) After checking that the beam axis of the source transducer and the beam axis of the hydrophone are colinear, locate the position on the beam axis where the received signal from the hydrophone, $V_h(r, t)$, where r is the radial coordinate and t is time, is a maximum. This point usually located at an axial distance equal to or greater than the focal length, or transition distance if source transducer is nonfocused.

NOTE: $V_h(r, t)$ is often expressed as

$$V_h(r, t) = V_p(r) V(t) / V_p(0) \quad (\text{Eq 7})$$

where $V_p(r)$ is the hydrophone voltage amplitude in volts at a radial distance r , and $V(t)$ is the hydrophone voltage waveform at $r = 0$.

- (4) Using this point as an origin, acquire two complete orthogonal diametric hydrophone profiles by recording the voltage amplitude as a function of position from the beam axis in 0.05 cm steps. A complete diametric profile includes all points for which the amplitude is greater than or equal to 5% of the voltage value (maximum) on the beam axis.
- (5) Integrate over the square of each point of these profiles, i.e., find S from

$$S = \frac{\pi}{N} \sum_{i=1}^N \left\{ \int_{-R}^R V_p^2(r) |r| dr \right\}_i \quad (\text{Eq 8})$$

where N is usually 2, $\pm R$ is the effective beam radius at the point where the voltage amplitude reaches 5% (or -26 dB) of the peak axis value, and r and dr have units of cm. (N would be increased if the profiles showed more than a 25% asymmetry; i.e., if the values obtained for each diametric profile differed from S by more than 25%.)

- (6) Find the mean square of the hydrophone voltage waveform at $r = 0$ over one pulse period T , where T is the reciprocal of the pulse repetition frequency. That is, find the quantity H in

$$H = T^{-1} \int_0^T V^2(t) dt \quad (\text{Eq 9})$$

[For a sinusoidal, continuous wave waveform displaying little evidence of finite amplitude distortion, $H = 0.5 V_p^2(0)$.]

- (7) If the ultrasonic power, W , in watts, is known at frequency f , the intensity response factor of the hydrophone would then be

$$K_f^2 = HS / W V_p^2(0) \quad V^2 W^{-1} \text{ cm}^2 \quad (\text{Eq 10})$$

Under the assumption of plane wave propagation, the end-of-cable sensitivity, M , is related to K_f^2 by

$$M = 0.01 (K_f^2 / \rho c)^{1/2} \text{ V/Pa} \quad (\text{Eq 11})$$

where ρ is in kg/m^3 and c is in m/s . This assumption seems to be valid in the region of these measurements.

Also see [B8], [B15], [B23], [B25], [B27], and [B39].

1.4.3 Ultrasonic Absolute Power Transfer Standard

1.4.3.1 Ultrasonic Field Parameter Produced. Acoustic power (diagnostic range).

1.4.3.2 Phenomenon Involved. Secondary ultrasonic power transfer standard using a calibrated lithium niobate transducer system.

1.4.3.3 Ultrasonic Frequency Range for Which the Technique Is Applicable. 1.5 MHz to 21 MHz in 1 MHz increments beginning at 1.5 MHz.

1.4.3.4 Ultrasonic Field Configuration for Which the Technique Is Applicable. Field radiated by unfocused plane circular disk transducer.

1.4.3.5 Temporal Resolution. System generates an ultrasonic beam for which the temporal average acoustic power is known. Continuous wave operation only.

1.4.3.6 Spatial Resolution. Not applicable.

1.4.3.7 Range Over Which the Acoustic Power Is Produced. 1 mW to 1000 mW, temporal average, CW.

1.4.3.8 Uncertainty of Technique. $\pm 3\%$ (1.5–6 MHz); $\pm 7\%$ (6–16 MHz); $\pm 12\%$ (16–21 MHz).

1.4.3.9 Construction Details. The transfer standard consists of one multiple-frequency transducer and an external adjustable impedance-matching network. The transducer is cylindrical in shape, with the piezoelectric element and an electrical connector at opposite ends. The air-backed 36° Y-cut lithium niobate element has an overall diameter of 25.4 mm and a circular active area 15.9 mm in diameter. The stainless steel housing is 30 mm in diameter and 114 mm long, including the BNC connector. Usually connected to the transducer by a 2 m length of RG-58 cable, the matching network is contained in a $10.5 \text{ cm} \times 20 \text{ cm} \times 29 \text{ cm}$ box.

1.4.3.10 Electronic Details. In order to obviate user-supplied, rf-voltage-measurement equipment, a half-wave rectifier circuit is built into the transducer. A single cable interconnects transducer and matching network; circuitry in the matching network provides for the connection of a user-supplied 10 M Ω dc voltmeter, which then indicates the level of rf energy present at the transducer. The matching network is a wide-range, low-loss network of conventional design. The network is driven by a user-supplied 50 Ω high spectral purity continuous-wave rf source.

1.4.3.11 Procedure for Performing Measurements. The transfer standard is supplied with a table of dc voltages corresponding to 15 calibration points, where a calibration point is a level of output power and an operating frequency chosen in advance by the customer. To obtain a particular specified level of transducer output, the user adjusts the output level of the rf source until the specified dc voltmeter reading is obtained.

Also see [B14].

1.4.4 Hydrophone Calibration Using Nonlinear Propagation

1.4.4.1 Hydrophone Parameter Measured. End-of-cable sensitivity at several frequency points.

1.4.4.2 Phenomenon Involved. Nonlinear propagation in water—the transfer of energy from a wave of a certain frequency to its harmonic components.

1.4.4.3 Ultrasonic Frequency Range Over Which the Technique Is Applicable. 1 MHz to 70 MHz.

1.4.4.4 Ultrasonic Field Configuration for Which the Technique Is Applicable. The end-of-cable sensitivity of a hydrophone is measured under plane wave conditions.

1.4.4.5 Frequency Resolution. Calibration is performed at frequencies that are multiples of the fundamental frequency (e.g., 1 MHz).

1.4.4.6 Applicable Hydrophone Parameter Range. End-of-cable sensitivities above $\cong 10^{-9}$ V/Pa can be measured, but to determine the sensitivity over a wide frequency range in a single measurement the sensitivity should be at least 10^{-8} V/Pa.

1.4.4.7 Sensitivity of Technique. The test acoustic pressure is typically 0.5 MPa, so the output voltage in volts (peak) is $0.5S$, where S is the hydrophone sensitivity in 10^{-6} V/Pa. The signal at harmonic frequencies of the fundamental component is less than this by a factor roughly equal to the harmonic number.

1.4.4.8 Reproducibility. $\leq 8\%$ at all frequencies for sensitivities of 10^{-7} V/Pa or greater.

1.4.4.9 Construction Details

- (1) *Items purchased:* Data acquisition system, signal generator, rf power amplifier, unfocused source transducer (resonant, say, between 1 MHz and 8 MHz), small computer (e.g., microcomputer or programmable calculator). Optimum transducer diameter (in mm) is the lesser of $90f^{-3/2}$ and $25(l/f)^{1/2}$, where l is the length of the tank in meters, and f is the frequency in MHz. An rf voltage of 600 V peak into a $50\ \Omega$ impedance transducer is required (200 V peak into $\approx 20\ \Omega$ at 5 MHz).
- (2) *Items constructed:* Mounts for the hydrophone and transducer—providing for rotation of each about the two axes orthogonal to the propagation direction. Test tank—approximately $1 \times 0.3 \times 0.3$ m, providing support for hydrophone/transducer mounts and varying of the separation.

1.4.4.10 Electronic Details. *Data acquisition system*—to determine the harmonic amplitudes at multiples of the transducer frequency, e.g., digitizer, spectrum analyzer, or an oscilloscope with a set of narrowband electrical filters.

Signal generator—to provide (gated) sinusoidal output at the transducer resonant frequency. See [B5] and [B7], Section 4.2, for further details.

1.4.4.11 Procedure for Performing Measurements. All measurements are made with the hydrophone positioned on the acoustic axis of the transducer.

- (1) Determine the Rayleigh length (r_o) of the transducer from $r_o = \pi a^2/\lambda$, where a is the effective transducer radius and λ the acoustic wavelength.
- (2) Choose a position in the field where $R_m \geq 1$ ($R_m = z/r_o$, where z is the propagation distance). Set the transducer drive voltage to a low value (U_1), adjust transducer and hydrophone for maximum hydrophone output, and measure this output at the fundamental frequency (peak voltage V_1). If the output voltage at any harmonic frequency is greater than 10% of V_1 , then reduce the transducer voltage and repeat this step.
- (3) Increase the transducer drive voltage to a high value (U_2) and measure the hydrophone output at the fundamental and harmonic frequencies [V_2 and $V_2(n)$, respectively]. Determine $L = V_2 U_1 / V_1 U_2$, and if $L > 0.5$ increase the drive voltage and repeat the measurement of U_2 , V_2 , and $V_2(n)$.
- (4) Calculate x by iteration from

$$x = \sinh(A + Bx) + B^2 x^3 \coth(A + Bx) \quad (\text{Eq 12})$$

where

$$A = \alpha r_o (1 + R_m^2)^{1/2} \ln [R_m + (1 + R_m^2)^{1/2}] \quad (\text{Eq 13})$$

and

$$B = L/2 \exp(\alpha z) \quad (\text{Eq 14})$$

α is the attenuation coefficient at the fundamental frequency in Np m^{-1} .

Calculate S_1 , the hydrophone end-of-cable sensitivity at the fundamental frequency, from

$$S_1 = 3.5 \pi V_2 x / \alpha \rho c^2 \lambda \quad (\text{in V/Pa}) \quad (\text{Eq 15})$$

where c is the wave velocity and ρ is the density of water.

- (5) Calculate values of S_n , the end-of-cable sensitivity at a frequency n times the fundamental frequency, from

$$S_n/S_1 = V_2(n) \sinh[n(A + Bx)] / V_2 x [1 - nB^2 x^2 \coth[n(A + Bx)]] \quad (\text{Eq 16})$$

- (6) Repeat steps (2) through (5), using different distances and drive voltages (U_2), and take the mean value for the sensitivities.

NOTE: Bacon ([B6] and [B7]) gives alternative and more accurate methods for steps (4) and (5). The accuracy of S_1 is generally better than that of S_n , so several different fundamental frequencies could be used and step (5) omitted. This would be of particular interest if calibrations were required only below 10 MHz. It is advisable to check the linearity of the transducer/hydrophone system by measuring V as a function of U for a propagation distance of a few millimeters.

If a long, thin tank is used, it may be necessary to line the walls with acoustic baffles to prevent stray reflections from interfering with the field at the hydrophone. The water in the tank should have been freshly deionized or distilled so that its acoustical properties correspond to those derived from the literature.

1.4.5 Hydrophone Calibration by Substitution in a Sawtooth Wave

1.4.5.1 Hydrophone Parameter Measured. End-of-cable sensitivity of a hydrophone at several frequencies, relative to a reference hydrophone.

1.4.5.2 Phenomenon Involved. Acoustic wave is generated by nonlinear propagation.

1.4.5.3 Ultrasonic Frequency Range Over Which the Technique Is Applicable. 1 MHz to 100 MHz, assuming a calibrated reference hydrophone is available over this range.

1.4.5.4 Ultrasonic Field Configuration for Which the Technique Is Applicable. The end-of-cable sensitivity of a hydrophone is measured under plane wave conditions.

1.4.5.5 Frequency Resolution. Intercomparison is achieved at frequencies that are multiples of the fundamental frequency (e.g., 1 MHz).

1.4.5.6 Applicable Hydrophone Parameter Range. End-of-cable sensitivities above $\cong 10^{-9}$ V/Pa can be measured, but it is difficult to measure the response over a wide range of frequencies if the sensitivity is less than 10^{-8} V/Pa.

1.4.5.7 Sensitivity of Technique. The test acoustic pressure is typically 0.2 MPa at the fundamental frequency, so the output voltage in volts (peak) is $0.2S$, where S is the hydrophone sensitivity in 10^{-6} V/Pa. The output voltage at the harmonic frequencies is less than this by a factor roughly equal to the harmonic number.

1.4.5.8 Reproducibility. 2% for sensitivities of 10^{-7} V/Pa or greater. The random uncertainties (95% confidence level) for a 1 MHz fundamental frequency typically vary from 2% to 4% between 1 and 15 MHz.

1.4.5.9 Construction Details

- (1) *Items purchased:* Data acquisition system, signal generator, rf power amplifier, unfocused source transducer (resonant at, say, 1 MHz), calibrated reference hydrophone (with amplifier, if necessary).
- (2) *Items constructed:* Mounts for the hydrophone and transducer — providing for rotation of each about the two axes orthogonal to the propagation direction. Test tank — approximately $1 \times 0.3 \times 0.3$ m, providing support for hydrophone/transducer mounts and varying of the separation.

1.4.5.10 Electronic Details. *Data acquisition system:* to determine the harmonic amplitudes at multiples of the transducer frequency — e.g., digitizer, spectrum analyzer, or oscilloscope with a set of narrowband electrical filters.

Signal generator: to provide (gated) sinusoidal output at the transducer resonant frequency.

1.4.5.11 Procedure for Performing Measurements

- (1) Place the calibrated hydrophone in the transducer field, and adjust for maximum received signal.
- (2) Increase the transducer drive voltage until a sawtooth waveform is received (containing many frequency components), and determine the amplitude of each harmonic component in volts.
- (3) Keeping the transducer drive voltage constant, place the uncalibrated hydrophone in the same field position and adjust for maximum signal. Determine the amplitude of each harmonic component.
- (4) For each frequency, determine the ratio of the amplitudes measured in steps (3) and (2) to obtain the end-of-cable sensitivity of the uncalibrated hydrophone. For further information, see [B5], [B7], and Smith and Bacon.³

NOTE: If a long, thin tank is used, it may be necessary to line the walls with acoustic baffles to prevent stray reflections from interfering with the field at the hydrophone. If a fundamental frequency of 1 MHz is used, it may be necessary to use a larger tank in order to achieve the required sawtooth waveform (e.g., a tank 1.8 m in length, with a transducer 40–50 mm in diameter driven with 100 V peak). It is advisable to check the linearity of the hydrophone in a separate measurement (as in any other calibration technique).

³Smith, R.A. and Bacon, D. R., A Multiple-Frequency Hydrophone Calibration Technique, to be published in May 1990, vol. 87, pp. 2231–2243, *Journal of the Acoustical Society of America*.

1.4.6 Pulsed Technique for Hydrophone Frequency Response Measurement

1.4.6.1 Hydrophone Parameter Measured. End-of-cable sensitivity as a function of frequency.

1.4.6.2 Phenomenon Involved. Piezoelectric generation and detection of broadband, plane wave pulses.

1.4.6.3 Ultrasonic Frequency Range Over Which the Technique Is Applicable. 1 MHz to 10 MHz.

1.4.6.4 Ultrasonic Field Configuration for Which the Technique Is Applicable. Plane wave.

1.4.6.5 Frequency Resolution of Technique. Determined by waveform processing method (e.g., spectrum analyzer, FFT). For a spectrum analyzer, the frequency resolution is determined by the bandwidth of the input filter. For an FFT, the frequency resolution is $\Delta f = 1/N\Delta t$, where N is the number of data points in the sampled time waveform array, and Δt is the time between samples. For example, if $\Delta t = 10$ ns and $N = 1024$, $\Delta f \approx 100$ kHz. A typical range for Δf is 10–250 kHz.

1.4.6.6 Range Over Which Sensitivity Is Measured. End-of-cable sensitivities greater than -270 dB re 1 V/ μ Pa ($\approx 3 \cdot 10^{-8}$ V/Pa).

1.4.6.7 Sensitivity of Technique. Typically, changes of ≈ 0.2 dB in end-of-cable sensitivity can be detected.

1.4.6.8 Construction Details

(1) *Items purchased:*

- (a) High-voltage pulse generator
- (b) Data acquisition/spectral analysis system

(2) *Items constructed:*

- (a) Thick disk source transducer, 5–7 cm diameter $\times$ 1–3 cm thick (e.g., lead zirconate titanate) (see Fig 9 and [B22] for details).
- (b) Attenuator for monitoring source voltage. In Fig 9 a capacitive divider is shown.
- (c) Water-filled test tank and holder and positioner for source transducer and hydrophone.

1.4.6.9 Electronic Details

- (1) Either swept filter or FFT-based systems can be used for the spectral analysis. In the latter case, the hydrophone phase as well as amplitude response versus frequency can be obtained. An external hydrophone amplifier having known gain and frequency response

Fig 9
Diagram of Source Transducer

