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WIDEBAND CHARACTERIZATION OF ULTRASOUND TRANSDUCERS AND MATERIALS USING TIME DELAY SPECTROMETRY

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This paper describes a procedure based on a swept frequency technique which provides wideband characterization of ultrasound transducers and materials. The procedure utilizes the Time Delay Spectrometry (TDS) principle and features significantly improved signal to noise ratio when compared to other conventional swept frequency systems. The experimental data illustrate the main advantages of the technique. In particular, they demonstrate the use of TDS to determine key parameters of acoustic transducers including transmitting and receiving frequency response, directivity patterns, and effective aperture. In addition, measurements of material acoustic attenuation are shown as a virtually continuous function of frequency.

1. Introduction

Several methods for evaluating ultrasonic transducer performance and measuring material acoustic parameters are currently in use [1–4]. Transducer performance evaluations are needed to provide quantitative data for any ultrasonic exposimetry related measurements. Such measurements require not only the knowledge of the absolute frequency response of the acoustic sources or receivers, but also information on their directivity patterns and associated effective apertures [5]. The desing and testing of transducers involves acoustic measurements on auxiliary materials. Those materials are used for instance as acoustic windows baffles, reflectors, and sound absorbers or anechoic coatings. In particular, development of mechanically scanned diagnostic ultrasound devices, involves the critical choice of the coupling liquid in which the transducer is immersed [6, 7]. Although it may first appear that a "lossless" liquid would be the best choice, it is often desirable to have some attenuation in order to reduce reverberation artifacts from multiple acoustic reflections within the probe assembly. Therefore, knowledge of liquid attenuation properties, especially over the entire diagnostic frequency range is of importance to transducer designers and manufacturers.

The techniques and procedures for transducer characterization are closely related to those used for evaluation of material acoustic parameters. In general, the characterization procedures are carried out either in the time of frequency domains. Since the goal of this paper is to discuss applications of a spectral analysis technique i.e. measurements carried out in the frequency domain, this is the primary technique discussed here. However, it may be appropriate to briefly point out the principle and potential problems associated with time domain measurements.

The standard procedure for characterizing an ultrasonic transducer in the time domain involves determining the transducer's impulse response. Two basic approached to the measurement of the impulse response can be distinguished. The first one is based on reflection and is known as the pulse-echo technique [2]; the second approach involves a small hydrophone probe [8], positioned at the desired point in the field of the acoustic source. Both approaches depend on the transmitter-receiver separation and off-axis location. The primary advantage of the pulse-echo technique is that it is relatively simple, however it is difficult to comprehensively characterize an ultrasonic transducer by the pulse-echo method alone. This is because the measurements combine the acoustic sources' transmitting and receiving characteristics. In addition, the results are modified due to the changes in the electrical load as a function of frequency. Time domain approaches also suffer from the fairly low signal to noise ratio inherent to a broadband measurement system, especially when the measurements are performed at relatively low acoustic pressure levels (0.1–1 kPa), such as those encountered during measurements of the off-axis field distribution. Many of these disadvantages may be overcome by using frequency domain measurements.

Quantitative measurements of transducer frequency characteristics require a free-field environment, which may be obtained by using an anechoic water tank with absorber lined side and bottom surfaces. However, if continuous wave (CW) excitation is used, the dimensions required of the water tank increase as the frequency decreases, making the anechoic water tank an impractically costly proposition. To overcome that limitation, the gated tone burst technique is widely used to facilitate the measurements in a relatively small water tank [9]. It is now possible (e.g. using a programmable function generator) to generate a tone burst of any desired frequency. However, in practice, at the biomedical ultrasonics range of frequencies, measurements are usually carried out at discrete frequencies, often separated by more than one megahertz. This is inadequate in several applications, in that it may overlook steep, critical variations in the frequency response [10]. To alleviate this problem, a unique swept frequency approach was employed that allowed free field measurements. The approach uses the Time Delay Spectrometry technique originally proposed by Heyser over two decades ago for the analysis of loudspeaker performance [11]. Subsequently, the technique gained attention for quantitative measurements of acoustic field parameters at medical ultrasonics frequencies [12–14]. In the following section the Time Delay Spectrometry principle is briefly reviewed, and the key acoustic parameters characterizing ultrasound transducers are introduced.

Section 3 presents details of the measurements approach, including measurement arrangement; the results of characterization of ultrasound transducers and acoustic materials are given in Section 4.

2. Time Delay Spectrometry and acoustic parameters

Time Delay Spectrometry (TDS) Principle

Time Delay Spectrometry (TDS) principle is illustrated in Fig. 1. The TDS concept is based on converting the given propagation time (here between the acoustic source and the receiver hydrophone probe) into a carefully controlled, prescribed frequency shift. This is accomplished by using a linearly swept sinusoidal signal to excite a wideband transducer, always maintaining a constant frequency sweep rate. By accounting for the time delay between the transmitter and the receiver, it is possible to isolate the direct acoustic path signal from any reflections from the sides and bottom of the water tank, through narrow band filtering. In this way, free-field measurements can be performed in an acoustically reflective environment. The signal measured is detected by a wideband, calibrated PVDF hydrophone probe and after appropriate processing, can be displayed in terms of frequency response, angular response, and attenuation spectrum. The most significant advantages of the technique are that the responses and measured

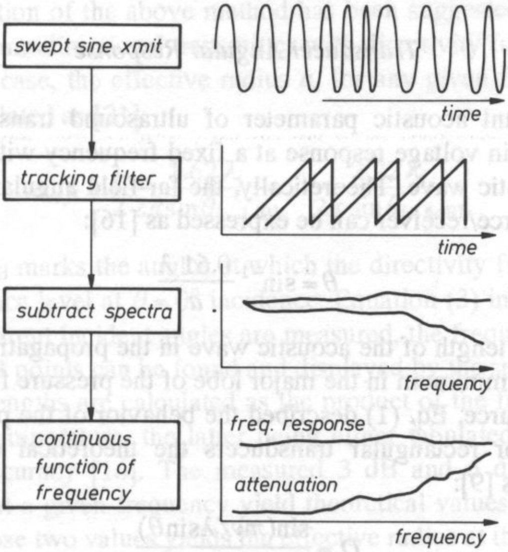

FIG. 1. Time Delay Spectrometry principle.

as a virtually continuous function of frequency, and since the receiver signal is narrow band filtered, TDS offers improved signal to noise ratio when compared with any other measurements technique.

Transducer Frequency Response

Free-field end-of-cable frequency response as a function of frequency is one of the key parameters characterizing ultrasound transducers [8 – 10, 15]. The receiving voltage response is defined as a ratio of the electrical output voltage measured at the terminals of the receiver (hydrophone) with a specified load, and the acoustic pressure at normal incidence acting on the receiver, expressed in units volts per micropascal. Free field transmitting voltage response is expressed in units dB re 1 μPa per volt at a given distance and describes the transducer properties as an acoustic source. Its magnitude denotes an acoustic pressure amplitude generated at a given axial distance by the piezoelectric source excited with one volt.

Transducer Angular Response

Another important acoustic parameter of ultrasound transmitters and receivers describes variations in voltage response at a fixed frequency with varying angle of incidence of the acoustic wave. Theoretically, the far-field angular response of a planar circular acoustic source/receiver can be expressed as [16]:

$$\theta = \sin^{-1}\frac{0.61\,\lambda}{a} \tag{1}$$

where λ is the wave length of the acoustic wave in the propagating medium, θ denotes the angle of the first minimum in the major lobe of the pressure field and a is the effective radius of the source. Eq. (1) described the behavior of the piston in a rigid planar buffle. Similarly, for rectangular transducers the theoretical expression describing directivity function is [9]:

$$D = \frac{\sin(\pi w/\lambda \sin\theta)}{\pi w/\lambda \sin\theta} \tag{2}$$

where w is the width of the piezoelectric element and angle θ is defined in Fig. 4.

There are two other physical models which predict the angular response. The soft (pressure-release) baffle model modifies the Eq. (1) by introducing a $\cos\theta$ term, (i.e. Eq. (1) and (2) are multiplied by this cosine term) [16]. It is worth noting that it has been reported that this term is needed in the case of a very narrow strip acoustic radiator (e.g. single element in an array system, with w of the order of 0.3 mm) to obtain an agreement with the experimentally determined angular responses [17]. Similarly, unrestricted piston model modifies the response given by Eq. (1) and (2) by multiplying them by a term $[(1 + \cos\theta)/2]$ [18]. In general, the effect of the cosine terms is to narrow the main lobe and force the response to be zero at 90° incidence angle.

Effective aperture size of ultrasonic transducers

It is well known that the area of transduction and the geometrical area ot the ultrasound transducer are seldom identical [15, 19]. The empirically determined area (usually termed the effective area) varies with frequency, and often differs markedly from the geometrical area of the sensor element [5, 15]. The importance of knowing the effective area of ultrasound sources and receivers is well recognized – this area is needed in order to determine (and correct, if possible) the error introduced by it in a measurement of the spatial and temporal intensity of the acoustic field radiated by an acoustic source [5, 20]. While there are several theoretical expressions (see previous subsection) on which the experimental determination of the effective area of circular transducers can be based, the most widely used one assumes that the angular response is sufficiently well approximated by Eq. (1). Once the angle corresponding to the first minimum in the major lobe of the pressure field is experimentally determined, calculation of the effective radius of the transducer at a given frequency can be carried out.

A slight modification of the above method has been suggested in [2]. It is valid in the case of a nearly omnidirectional transmitter with directivity function not exhibiting any minima. In such case, the effective radius a_e for any given frequency f_i can more conveniently be calculated as [21]:

$$a_e, f_i = \frac{1}{2}\,\frac{1.62\,\lambda_i}{2\pi\sin\theta_{[-3\mathrm{dB}]}} + \frac{2.22\,\lambda_i}{2\pi\sin\theta_{[-6\mathrm{dB}]}} \tag{3}$$

where $\theta_{-3\mathrm{dB}}$ and $\theta_{-6\mathrm{dB}}$ marks the angles at which the directivity function is 3 and 6 dB down from its reference level at $\theta = 0°$ incidence. Equation (3) indicates that if spectra corresponding to different incident angles are measured, the frequencies corresponding to – 3 dB and – 6 dB points can be found and displayed by the spectrum analyser. The corresponding wavelengths are calculated as the product of the frequencies and sound velocity at a given temperature, the latter being either tabulated or calculated to the desired degree of accuracy [16]. The measured 3 dB and 6 dB half angles of the transducer response at a given frequency yield theoretical values of the transducer radius. The mean of those two values yields the effective radius at this frequency.

3. Materials and methods

This section describes the measurement system used to determine the acoustic parameters of ultrasound transducers and to measure the attenuation of various materials.

Measurement Arrangement

The measurement arrangement is shown in Fig. 2. An HP 3585A spectrum analyser is used to drive (via ENI 240LF power amplifier) a purpose built wideband PVDF

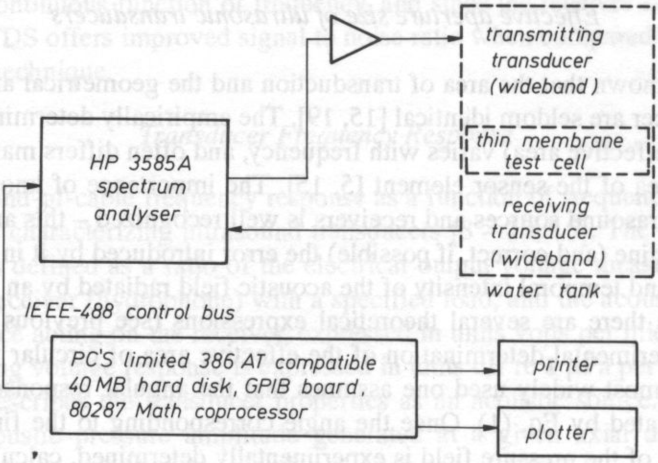

FIG. 2. Experimental setup.

transmitter [15]. This 10 mm diameter transmitter was designed to provide a wideband, uniform transmitting response. The acoustic signal is received by wideband PVDF hydrophone of needle-type design with a 0.6 mm diameter (Danish Institute of Biomedical Engineering, Copenhagen, Denmark) or by a 9 micron membrane type design with a 0.4 mm diameter (Sonic Technologies, Horsham, PA). Both probes exhibit smooth (to within ± 1.5 dB) frequency characteristics and predictible angular responses, and had been reciprocity calibrated. A review of the design and properties of hydrophones especially suited for ultrasound field measurements has been published [21]. The spectrum analyser is controlled by a 386–AT compatible computer over an IEEE-488 bus. A comprehensive description of the selection of appropriate TDS parameters such as sweep rate, resolution bandwidth, and sweep time is given in [14]. Further details of the scanning tank are given in section Attenuation Measurements.

Wideband Characterization of Ultrasound Transducers

Frequency response–hydrophone calibration technique. The primary wideband calibration of the hydrophone probes was carried out using a combined TDS and reciprocity technique [23, 24].

After detection by the reciprocity calibrated hydrophone probe, the signal was stored in one of the two built-in memories of the spectrum analyser and then displayed on its screen. Next, the calibrated hydrophone was replaced by the unknown hydrophone. Again, the signal detected by this hydrophone was stored in the spectrum analyser's second memory and both signals were transferred to the IBM PC computer which subtracted the two spectra, compared the result with the absolute frequency response of the reciprocity calibrated hydrophone probe and plotted a hard copy of the resulting free field, receiving frequency response of the unknown hydrophone.

Angular response. The angular responses or directivity patterns were determined in the following way. Relative spectra of the hydrophone probe (or acoustic source) as a function of acoustic pressure wave incidence angle were recorded, displayed on the screen of the spectrum analyser, and subsequently transferred to the IBM PC for a hard copy print out. The print outs were available as incidence angle versus frequency or as a more conventional representation in terms of polar diagrams [8].

Effective aperture size. The incidence angle versus frequency plot obtained during the assessement of the angular response was used to determine the effective aperture size of the differently shaped acoustic sources and hydrophone probes. The effective apertures were calculated based on the Eqs. (1) – (3) (Section 2).

To minimize possible errors, all measurements reported here were performed beyond the position of the last axial maximum on the acoustic axis of the wideband 10 mm diameter PVDF acoustic source [15]. The temperature of distilled, degassed water in the tank was temperature controlled ± 0.5 °C, partly to minimize the changes in the sound speed in the water and thus between the measurements taken over a period of time, and partly to minimize the variation in PVDF transducers with temperature. The uncertainty in the axial distance measurements as well as the uncertainty in the alignment of the hydrophones in the plane perpendicular to the acoustic axis of the transmitter, assuming constant propagation velocity in water, was estimated to be better than 0.15 mm. The deflection angle θ was controlled to within 0.2°C.

Attenuation Measurements using TDS

In order to measure the excess material attenuation as a function of frequency, the TDS technique described above (Section 2) was used in the following way: first, the wideband transmitter, hydrophone, and HP3585A spectrum analyzer were set up in water as they would be for frequency response calibration (see section above). The spectral data from the water measurement were transferred from the spectrum analyzer to the controlling computer. Then, the test cell with material to be tested (described in detail below) was placed in the direct acoustic path. The resultant spectrum was then subtracted from the stored, "water-only" spectrum to yield the relative attenuation of the tested material as a function of frequency. Figure 2 shows the measurement arrangement used; in practice the transmitter/hydrophone distance was about 19 cm. The measurements reported here were primarily carried out on liquids, however, the acoustic attenuation of a 6 mm thick plate made of Sorbothane TM was also tested.

It is important to realize that the attenuation results include the effects of both attenuation in the material, and reflection losses at the water/sample interface due to impedance mismatches. (The effect of membrane reflection in the test cell was minimal; this was confirmed using a test cell filled with water only). The reflection loss was accounted for using a separate measurement of the liquid's specific acoustic impedance, using the density and the sound speed determined from a modified differential distance technique [25]. Computer routines calculated and subtracted the reflection loss estimate from the measured data, leaving only the attenuation component. Based on operator input as to the thickness of the test cell, the computer normalized the results to values of dB/cm.

Test Cell Design and Construction. The critical component in the attenuation measurement system is the test cell, which is designed to maintain the liquids as thin, uniform layers in the acoustic path. The eight centimeter square fluid area was large enough to be considered essentially of infinite extent when placed near the transmitting transducer. The key to the design of the test cell was the use of shrink-wrap plastic, which provided a thin yet strong membrane. The plastic film was held in place using 3 mm thick metal frames, and was sealed to the stiff Plexiglas shell structure using rubber cement. Then the membranes were carefully stretched taut using a heat gun. Caution was required, because overheating caused the membranes to rip open, requiring reassembly. The stretched membranes were about 18–20 μm thick, based on micrometer measurements of disassembled test cells. This 18 μm thickness could be considered negligible in comparison with the shortest wavelength of interest, approximately 100 μm at 15 MHz.

Once the membranes were sealed and stretched, the test cells were carefully filled with liquid through a fill hole using a hypodermic needle and syringe. In order to equalitze the hydrostatic pressure of the liquid against the membranes as the cell was filled, the cells were slowly dipped into the water tank during filling. This kept the membranes from bowing out; the fill hole was then sealed with a small set screw.

Several test cells were constructed with different thicknesses. In practice, there was a limit on the thickness of the test cells. Because the liquids used in the experiments had densities different from water, there was a tendency for the liquids to distort the test cells into a wedge shape when subjected to the hydrostatic pressure of the surrounding water. For example, if the liquid was denser than water, the test cells would sag. The thicker the test cell, the greated the hydrostatic effect and the greater wedge shaped distortion. Therefore, the thickest test cell used was 3 mm.

Scanning Tank Desing. The scanning tank had to meet certain specific requirements as to the geometry of the source, test cell, and receiver, and the alignment of the receiver with the plane of the acoustic source and test cells. The hydrophone probe was rigidly held in a machined slot using a set screw, thus ensuring that the probe was positioned perpendicular to the plane of the holder. In use, the holder was covered with a sound absorbing rubber to minimized reflections. The acoustic source (transmitter) holder was designed to permit the easy mounting of transmitters of different diameters and shapes. The acoustic axis of the transmitter could be aligned with the hydrophone, using a two-axis precision gymbal mount. (The alignment procedure is detailed below). With this gymbal mount, the angular position of the source was continuously adjustable over a ± 10° range with a resolution of 2 arc seconds. The transmitter assembly was moved perpendicularly to the receiver plane (along the Z – axis) using manually adjusted precision lead screw sliders. The test cell was mounted similarly to the transmitter, with a two-axis precision gymbal mount (± 6° angular range with 1 arc second resolution) on a manual Z – axis slider. The test cell and transmitter mounts were arranged such that they could be positioned independently along the Z – axis without interfering with one another.

Alignment procedures. Since one possible influence on the measured attenuation was the alignment of the test cell with respect to the acoustic path, specific alignment procedures were developed to insure that the transmitter, the test cells, and the receiver were indeed aligned. First, the hydrophone assembly was positioned such that the flat Plexiglas portion of the holder was in front of the transmitter. The transmitter was connected to a Panametrics PR5052 pulser, set for pulse-echo mode. The transducer assembly was angled until the return echo from the hydrophone holder was maximized. To align the cell, the same pulse-echo techniques were used, only this time, the test cell was angled until the reflections from the membrane surfaces were maximized. These reflections were typically 25 dB lower than the Plexiglas echoes. The alignment accuracy was estimated to be better than 0.2° for the transmitter/receiver alignment, and 0.4° for the test cell alignment.

4. Results

Wideband ultrasound transducer characterization. The frequency response of the given hydrophone transmitter combination was compared to that obtained from TDS reciprocity calibration. Fig. 3 shows a typical plot of 9 micron, 0.4 mm diameter, membrane hydrophone sensitivity versus frequency from 1–15 MHz. This result is typical of the 9 micron thick films [15]. The hydrophones are expected to have uniform frequency response up to 40 MHz and 110 MHz for the 25 μm and 9 μm films, respectively [15]. The cable length of the membrane hydrophones was 75 cm, and the terminating load was 1 MΩ in parallel with 30 pF (input impedance of the HP 3585A analyser). The peak pressure amplitudes used for the TDS calibration procedure ranged from 10 kPa to approx. 100 kPa, and indicate the excellent signal to noise ratio obtainable with the TDS technique.

Figures 4 and 5 show an example of directivity patterns for two different acoustic radiators, the first being a 4 MHz, 14 mm nominal diameter focused bowl transducer,

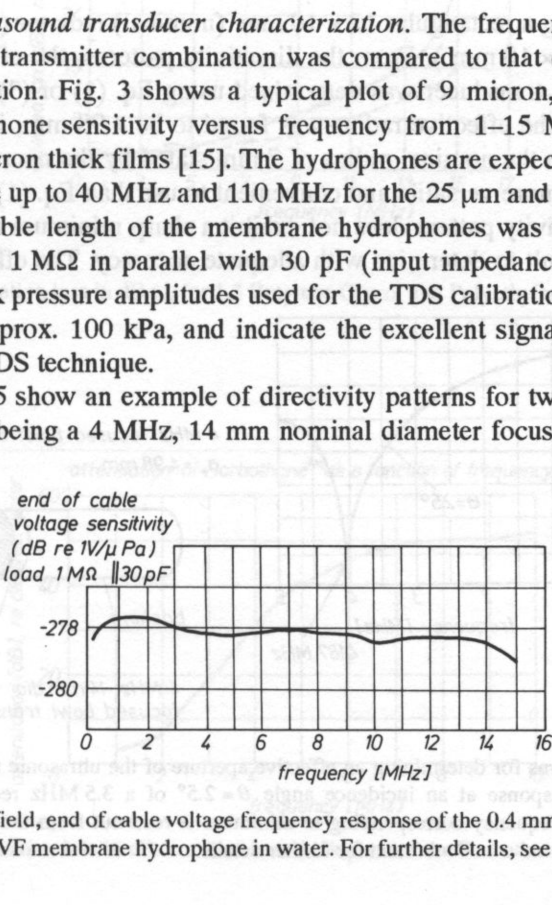

FIG. 3. Absolute, free-field, end of cable voltage frequency response of the 0.4 mm diameter, 9 μmm thick PDVF membrane hydrophone in water. For further details, see text.

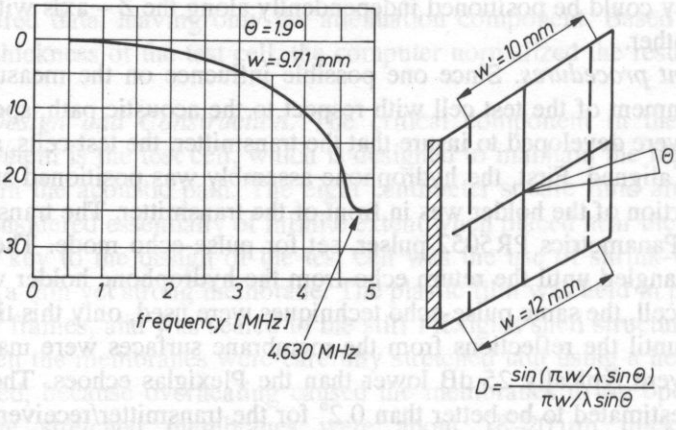

FIG. 4. Directivity patterns for determining an effective aperture of the ultrasonic transducer in water. As an example, angular response of a 4 MHz, 14 mm nominal diameter, focused bowl transducer at an incidence angle $\theta = 1.9$°C is shown. Frequency corresponding to minimum is read-out from the spectrum analyser. See text for further details.

and the second being a rectangular 12 × 10 mm (nominal) radiator (electroded surfaces had dimensions 10 × 10 mm). From the directivity patterns, the effective diameter of the circular focused transducer was determined using Eq. (1) or (3). In the case of the focused transducer the effective radius was found to be 4.98 mm, indicating a significant difference from the nominal radius of 7 mm stated by the manufacturer. In practice, Eq. (3) is often more versatile and convenient to use than Eq. (1), particularly when the measured directivity pattern does not exhibit a sharp minimum and first lobe minimum angle is difficult to determine with adequate accuracy. The effective width of the

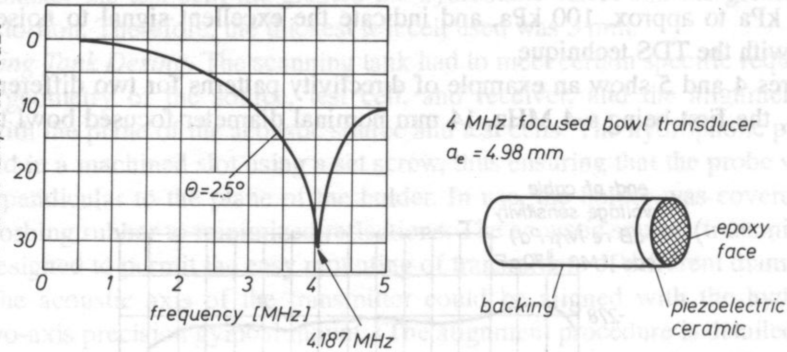

FIG. 5. Directivity patterns for determining an effective aperture of the ultrasonic transducers in water. As an example, angular response at an incidence angle $\theta = 2.5$° of a 3.5 MHz rectangular (12 × 10 mm) transmitter is shown. Frequency corresponding to minimum is read-out from the spectrum analyser. See text for further details.

rectangular piezoelectric transmitter (9.71 mm) was calculated using Eq. (2) with the input data obtained from the measurements (Fig. 4 and 5). As mentioned previously, the effective aperture of ultrasonic transceivers is, in general, frequency dependent and when needed should be determined at the relevant frequency.

Attenuation measurements. Several different liquids were tested, based on previous experience with diagnostic medical equipment. The actual measurements took only a few seconds to complete; the majority of the time was spent on filling the test cells. Figure 6 shows results of tests on selected liquids, over the frequency range 1 to 15 Hz. Graphs show attenuation loss in dB/cm for 1.3 Butylene Glycol, and Polyethylene Glycol 400. Other tested liquids included glycols, silicone oils, and "natural" oils such as mineral oil and castor oil. Figure 7 shows relative overall attenuation loss in 6 mm thick Sorbothane™ material over the frequency range 1 – 10 MHz.

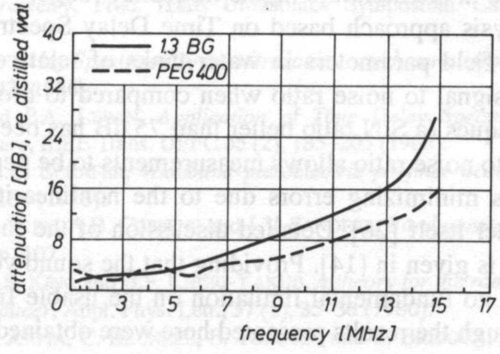

FIG. 6. Attenuation loss in dB/cm for 1.3 Butylene Glycol and Polyethylene Glycol 400.

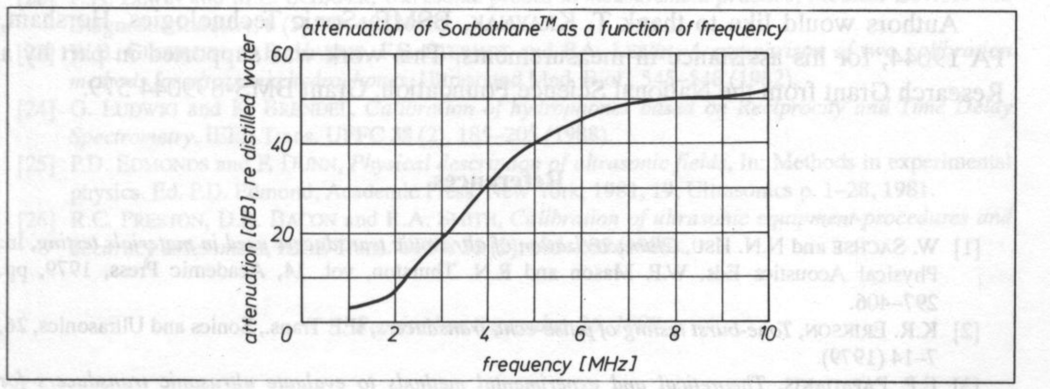

FIG. 7. Attenuation loss in dB/cm for 6 mm thick plate of the Sorbothane™ material.

Discussion and conclusions

Several applications of a spectral analysis technique based on the Time Delay Spectrometry principle have been illustrated in materials measurements and ultrasound transducer characterization. It has been shown that this technique provides a useful tool in determining essential acoustic parameters of ultrasound transmitters and receivers, and acoustic attenuation of different materials over wide range of frequencies. The results of attenuation measurements in liquids are in general agreement with those previously published [6] and show increasing attenuation with frequency, as is expected for viscous losses. The more viscous fluids generally showed higher levels of attenuation. Moreover, these parameters are available as a virtually continuous function of frequency. The results of attenuation measurements of 6 mm thick plate of absorbing material Sorbothane™ indicate 40 – 60 dB attenuation in comparison with water. No other data are available in the literature in this frequency range.

The spectral analysis approach based on Time Delay Spectrometry facilitates the determination of free-field parameters in water tanks of relatively small dimensions, and offers improved signal to noise ratio when compared to broadband time and frequency domain techniques (a S/N ratio better than 75 dB has been reported [12]). This relatively high signal to noise ratio allows measurements to be performed at low acoustic output levels, thus minimizing errors due to the nonlinearity of the propagation medium and transmitter itself [26]. Detailed discussion of the fundamental limitations of the TDS technique is given in [14]. Providing that the sound velocity is independent of frequency, there is no fundamental limitation on the usable frequency range of the TDS technique. Although the results presented here were obtained at the megahertz frequencies, the technique can be used at much lower frequencies. However, in practice, the low frequency limit of the measurements is restricted by the free space available (water tank dimensions).

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References

[1] W. SACHSE and N.N. HSU, *Characterization of ultrasonic transducers used in materials testing*, In: Physical Acoustics Eds. W.P. Mason and R.N. Thurston, vol. 14, Academic Press, 1979, pp. 297–406.

[2] K.R. ERIKSON, *Tone-burst testing of pulse-echo transducers*, IEE Trans., Sonics and Ultrasonics, **26**, 7–14 (1979).

[3] E.P. PAPADAKIS, *Theoretical and experimental methods to evaluate ultrasonic transducers for inspection and diagnostic applications*, IEEE Trans., Sonic and Ultrasonics, **26**, 155–26 (1979).

[4] N.G. PACE, *Impulse response of water loaded air-backed piezoelectric discs*, IEEE Trans. Sonics and Ultrasonics, **26**, 37–41 (1979).

[5] R.C. CHIVERS, L. BOSSELAR and P.A. FILMORE, *Effective area to be used in diffraction corrections*, J. Acoust. Soc. Am., 68, 80–84 (1980).

[6] A.R. SELFRIDGE, *Approximate material properties in isotropic materials*, IEEE Trans., EFFC **33** (3), 381–394 (1985).

[7] M.E. SCHAFER and P.A. LEWIN, *The influence of front-end hardware on digital ultrasonic imaging*, IEEE Trans., S-U 31 2, 295–306 (1984).

[8] P.A. LEWIN, *Miniature piezoelectric polymer ultrasonic hydrophone probes*, Ultrasonics, **16**, 213–216 (1981).

[9] R.J. BOBBER, *Underwater electroacoustic measurements*, Naval Research Laboratory, GPO, Washington, D.C. 1970.

[10] P.A. LEWIN, *Miniature ultrasonic probes for biomedical applications*, in Proc. of 1983 IEEE Ultrasonics Symposium, Atlanta October 1983, pp. 822–826.

[11] R.C. HEYSER, *Time Delay Spectrometry: an anthology of the works on measurement, analysis and perception*, AudioEngineering Society, 60 East 42 nd St.N.Y.10165, 1988.

[12] P.A. LEWIN, *Calibration and performances evaluation of miniature ultrasonic hydrophones using Time Delay Spectrometry*, Proc. IEEE Ultrasonics Symposium Chicago, Illinois, 1981, pp. 660–664.

[13] R.C. CHIVERS, *Time Delay Spectrometry for ultrasonic transducer characterization*, J. Phys. E: Sci. Instrum. **19**, 834–843 (1986).

[14] P.C. PEDERSEN and P.A. LEWIN, *Application of Time Delay Spectrometry for calibration of ultrasonic transducers*, IEEE Trans. UFFC **35** (2), 185–205 (1988).

[15] P.A. LEWIN and M.E. SCHAFER, *Wideband piezoelectric polymer acoustic sources*, IEEE Trans. UFFC, **35** (2) 175–184 (1988).

[16] L.E. KINSLER, A.R. FREY, A.B. COPPENS and J.V. SANDERS, *Fundamentals of acoustics*, 3rd edition John Wiley, 1982 pp. 107.

[17] A.R. SELFRIDGE, G.S. KINO and B.F. KHURI-YAKUB, *A theory for the radiation pattern for a narrow strip acoustic transducer*, Appl. Phys. Lett., **37** (1), 35–36 (1980).

[18] B. DELLANOY, H. LASOTA, C. BRUNEEL, E. TORQUET and E. BRIDOUX, Journal of Appl. Phys., **50**, 5189 (1979).

[19] P.A. LEWIN and R.C. CHIVERS, *Voltage sensitivity of miniature ultrasonic probes*, Ultrasonics, **21**, 282–283 (1983).

[20] G.R. HARRIS, *Hydrophone measurements in diagnostic ultrasound fields*, IEEE Trans. UFFC **35** (2), 87–101 (1988).

[21] Safety Standard for Diagnostic Sound Equipment, AIUM NEMA Standard Publication, No UL1–1981 (1981).

[22] P.A. LEWIN and M.E. SCHAFER, *Ultrasonic probes in measurement practice*, Medical Devices and Diagnostic Industry, **8** (5), 40–45 (1986).

[23] W.B. GLOERSEN, G.R. HARRIS, F.S. STEWART and P.A. LEWIN, *A comparison of two calibration methods for ultrasonic hydrophones*, Ultrasound Med. Biol., 545–548 (1982).

[24] G. LUDWIG and K. BRENDEL, *Calibration of hydrophones based on Reciprocity and Time Delay Spectrometry*, IEEE Trans. UFFC **35** (2), 185–205 (1988).

[25] P.D. EDMONDS and F. DUNN, *Physical description of ultrasonic fields*, In: Methods in experimental physics. Ed. P.D. Edmond, Academic Press, New York, 1981, 19, Ultrasonics p. 1–28, 1981.

[26] R.C. PRESTON, D.R. BACON and R.A. SMITH, *Calibration of ultrasonic equipment-procedures and accuracy assessment*, IEEE Trans. UFFC **35** (2), 185–205 (1988).

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