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# OVERCOMING THE ULTRASOUND DIFFRACTION ARTEFACT
# II. ATTENUATION ESTIMATION, CHARACTERISTIC IMPEDANCE AND NONLINEAR PROPAGATION

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ABSTRACT -- It is shown that a specially constructed hydrophone may be used with pulsed ultrasound fields to perform artefact-free measurements of attenuation, characteristic impedance, and nonlinear effects. The technology ensures that diffraction artefacts are minimized in the measurements.

## INTRODUCTION

In an accompanying paper (Costa et al, 1987-a), we have presented the theory and experimental support for a novel measurement technique which ensures that diffraction artefacts are minimal in practice (and entirely absent in theory). The technique is based upon a purpose-built PVDF hydrophone, which has been used for measuring attenuation and its frequency dependence, as well as for measuring the characteristic impedance (by reflectivity methods) of different materials. Some preliminary results when using this hydrophone for measuring nonlinear ultrasound pulsed fields are also shown.

## ATTENUATION MEASUREMENTS

A substitution method was used to estimate the transmission loss of castor oil and glycerine samples relative to water, using a 19 mm diameter, 3.5 MHz (nominal), focused transducer as a transmitter, and the PVDF hydrophone as a receiver. For comparison, we carried out the same series of measurements using a 6 mm diameter, 5.0 MHz (nominal centre frequency), focused transducer, and a point hydrophone as receivers. Both of these receivers were sufficiently wideband to enable measurements of transmission loss to be accurately made, with sufficient signal to noise ratio, in the 1 to 5 MHz frequency range utilised in these experiments.

The experimental set-up is shown in Figure 1. Measurements were performed in the 1 to 5 MHz frequency range, using sinusoidal tone-bursts of at least 20 cycles in duration. The transmitter was fixed and both the sample and the receiver could be translated axially. Experiments were performed in the following configurations: (1) sample at 3cm and receiver at 9cm from the transmitter; (2) sample at 6cm and receiver at 19cm from transmitter.

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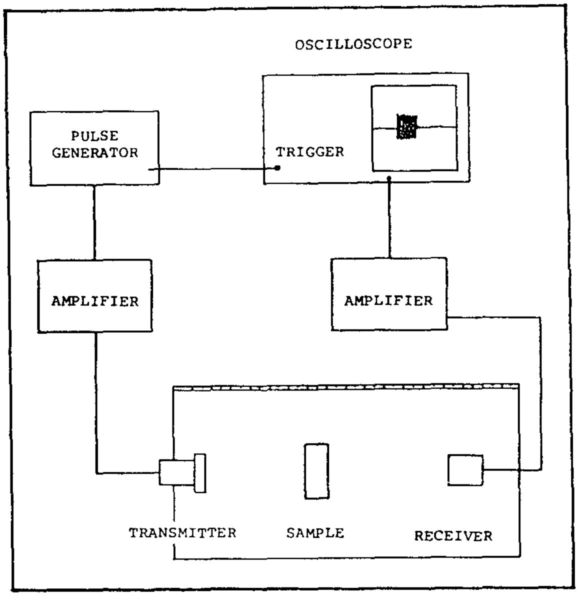
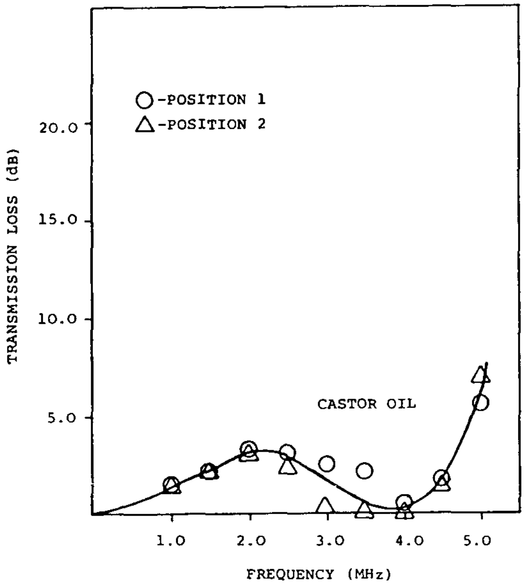



Fig. 1. Schematic experimental arrangement for measuring frequency dependence of attenuation.

Great care was exercised to ensure that measurements of the transmitted tone-bursts, at any frequency, were not corrupted by reflections from the walls of the sample vessel. However, in order to extract attenuation values from the transmission loss measurements, correction must be made for the transmissivity of the sample vessel walls. In principle, this is easily achieved by the use of our "diffraction-free" hydrophone, but was not considered essential in order to illustrate the points being made here. Hence, only transmission loss results are shown.

Figure 2 shows the variation of the transmission loss for castor oil and glycerine samples, as measured with a commercial 6 mm diameter focused receiver. The erratic and unexpected frequency dependence shows clear evidence of diffraction artefacts. Unnacceptably low and even negative transmission loss values are obtained around 4 MHz. Clearly not much credibility can be attached to such measurements, as they are totally swamped by diffraction effects.

Another possibility is to use a "point" (0.3 mm diameter) receiver, which removes the problems associated with possible phase-cancelation effects. Results for the same samples, as in Figure 2, are shown in Figure 3. Clearly, a much more acceptable frequency dependence of the transmission loss is obtained. However, there are quite significant differences between the results obtained in the two experimental configurations. Moreover, occasionally, zero, or negative, transmission losses can still be obtained. We conclude that diffraction artefacts are still present. For each sample, we have attempted to indicate the best fit (by eye) to <u>all</u> the data by a simple curve. Given the differences obtained in the two experimental configurations, it is questionable whether too much significance should be attached to such an



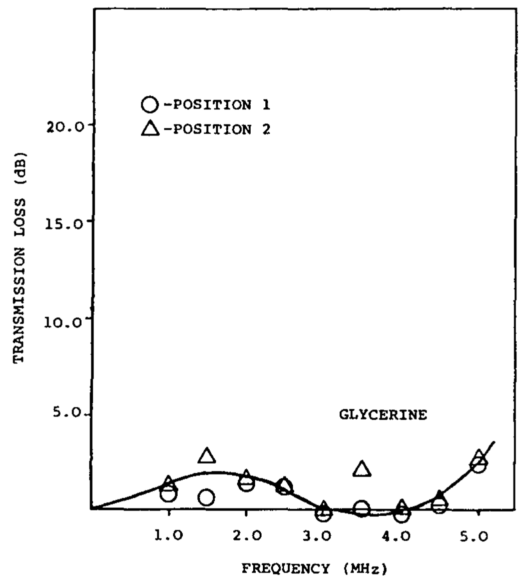




Fig. 2. Frequency dependence of the transmission loss of castor oil and glycerine samples, relative to that of an identical water sample, as measured with a 6 mm diameter focused PZT receiver for two different experimental configurations: position 1 - sample at 3 cm and receiver at 9 cm from transmitter; position 2 - sample at 6 cm and receiver at 19 cm from transmitter.

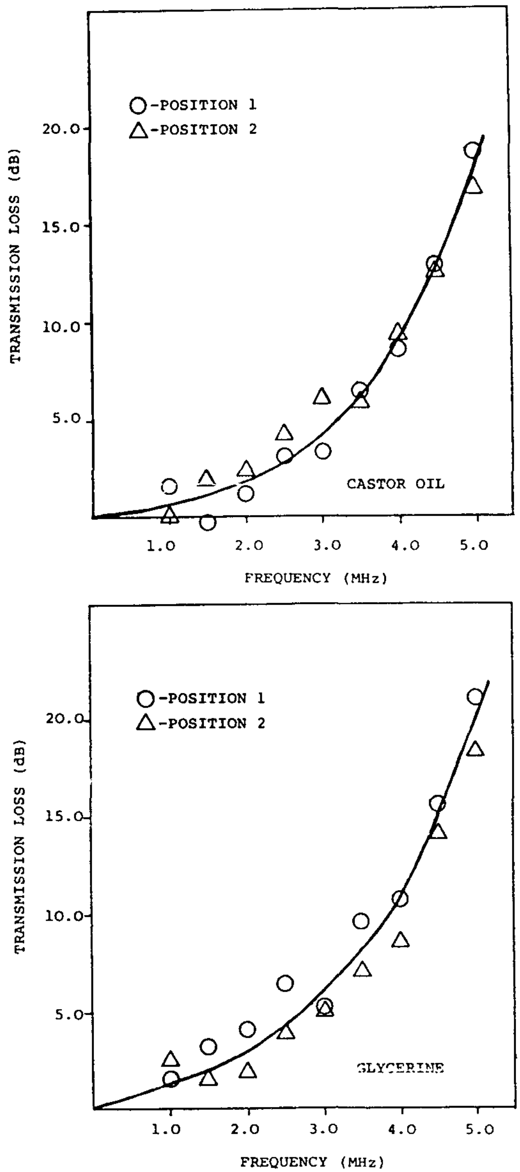



Fig. 3. Frequency dependence of the transmission loss of castor oil and glycerine samples, relative to that of an identical water sample, as measured with a point (0.3 mm diameter) hydrophone for the same positions as for figure 2.

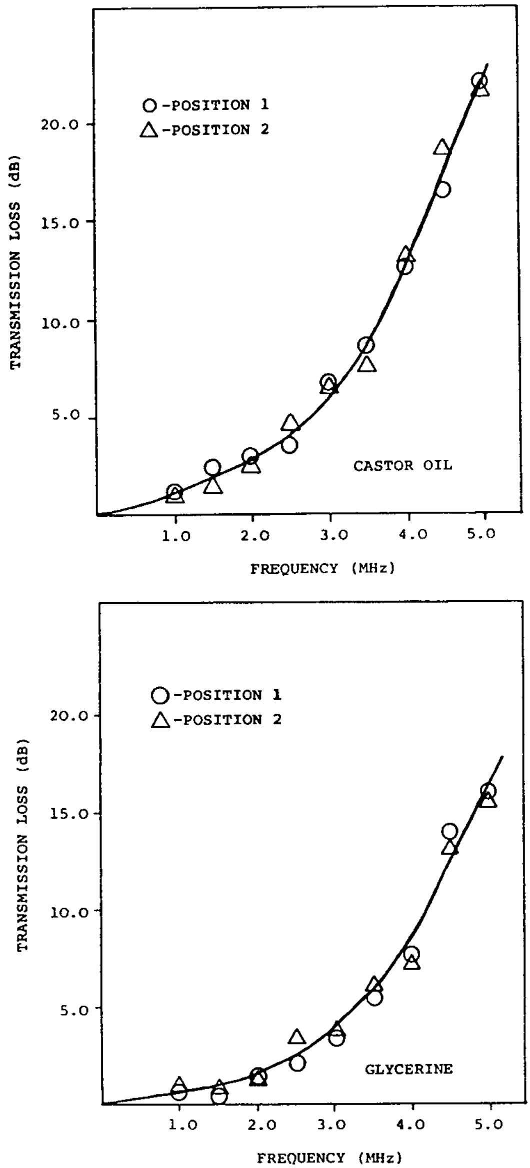



Fig. 4. Frequency dependence of the transmission loss of castor oil and glycerine samples, relative to that of an identical water sample, as measured with the purpose-built PVDF hydrophone for the same positions as for figure 2.

interpolation. However, the scatter about the smooth curve may be interpreted as giving some indication of the severity of the diffraction effects.

Results obtained with the PVDF "diffraction-free" hydrophone are shown in Figure 4 (previous page). For both samples, there is a quite good overlap between measurements obtained in the two different configurations. A simple curve can, quite readily, be fitted to the pooled data in each case. No unexpected frequency dependence emerges, and no unacceptable zero or negative transmission losses are seen.

As opposed to the demands of measuring with conventional transducers, our technique did not present setting-up difficulties, as the relative locations of the transmitter, sample and receiver did not significantly affect the results. Measurements may be carried out in the near or the far field, with focused or unfocused transmitters, as the circumstances dictate.

## CHARACTERISTIC IMPEDANCE

We have measured the reflectivity of perspex, with two different transmitters, one a 2.25 MHz (nominal), 19 mm diameter, focused transducer, and the other 3.5 MHz (nominal), 13 mm diameter, focused transducer. The schematic experimental arrangement can be seen in figure 5. The advantage of using the PVDF hydrophone in this measurement is that it can provide a measurement of both the transmitted (forward) and the reflected pulses. Thus absolute reflectivity can be assessed immediately, without the need for calibration against ideal reference reflector. Because the results are essentially those that would be obtained with 1-D planar wave fields, the (normal) reflectivity measurements may be related directly, without significant error, to the characteristic impedance of the reflector material.

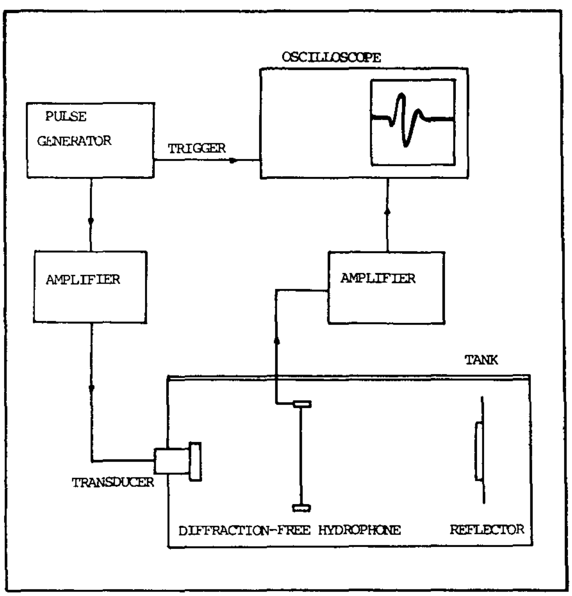



Fig. 5. Schematic experimental arrangement for measuring reflectivity with the purpose-built PVDF hydrophone. Reflector used: perspex.

It is interesting to observe that our preliminary results show some variation of the reflectivity with frequency, suggesting the feasibility of measuring the frequency dependence of the characteristic impedance by this technique. Since one contributor to this effect is the frequency dependence of the ultrasound (phase) velocity of the reflecting material, our approach suggests the possibility of a novel method for assessing velocity dispersion by a reflection technique!

Some preliminary measurements with perspex, giving $Z = 3.2 \times 10^{-6}$ kg/m$^2$/s using the 3.5 MHz (nominal centre frequency) transducer and $Z = 3.3 \times 10^{-6}$ kg/m$^2$/s using the 2.25 MHz (nominal centre frequency) transducer, show fair agreement with published values (Wells, 1977), although there is no suggestion of a frequency dependence for the characteristic impedance of perspex in the results of other workers.

## NONLINEAR ULTRASOUND PROPAGATION

Nonlinear propagation of ultrasound waves has become a major concern in medical ultrasound (Duck and Starrit, 1984) and several workers have been studying distortions in the observed waveform, which arise from nonlinear propagation and diffraction effects. According to Bacon (1986), a considerable knowledge of the acoustic waveform is required to avoid misinterpretation and errors in the determination of certain acoustic parameters due to the interaction of those effects.

We carried out a series of measurements with a 0.5 mm diameter bilaminar shielded PVDF hydrophone in order to observe and compare the waveforms for both linear and nonlinear fields. The results can be seen in figure 6. The field was produced by a 3.5 MHz, 19 mm diameter, 9 cm focused transducer and was probed at several axial locations. The scale was maintained the same for each series of measurements and, as expected for the linear focused field, the detected pulse changed as the probe moved away from the transmitter, showing visible diffraction effects before focus, maximum amplitude near the focus and decreasing rapidly in amplitude, but not changing notably in shape, after focus. For nonlinear propagation, the input power to the transmitter was increased by another 20 dB. At these increased power levels, the classical features of nonlinear wave propagation become evident: generation of harmonics beyond the spectral band of the input signal, with such "harmonic pumping" being dependent on both frequency and range from the transducer (Costa et al, 1987-b). With the point hydrophone, in the time domain, distortion of the received waveform resulting from nonlinear propagation is clearly observed, but is confused by diffraction effects particularly before the focus. As the pulse progresses through the focus, it changes its shape and amplitude completely: nonlinear propagation effects now become very marked, but are still confused by diffraction effects. Beyond the focus, there is a gradual decrease in amplitude, due to attenuation of the high frequency components, but also resulting from pulse spreading (diffraction): the two effects are difficult to unscramble.

Similar measurements of the same field were made using the "diffraction-free" hydrophone (oriented orthogonally to the beam direction) at the same locations as for the point hydrophone. The results are shown in figure 7. For the linear field, there was an invariant pulse throughout the field, showing no diffraction artefacts in the observed waveform. For the nonlinear field, however, the observed pulse gradually changes, with a sharp spike developing smoothly and progressively at the (temporal) centre of the pulse, decreasing in amplitude again due to attenuation. But it is quite clear that the distortion in the waveform is due entirely to nonlinear propagation, without

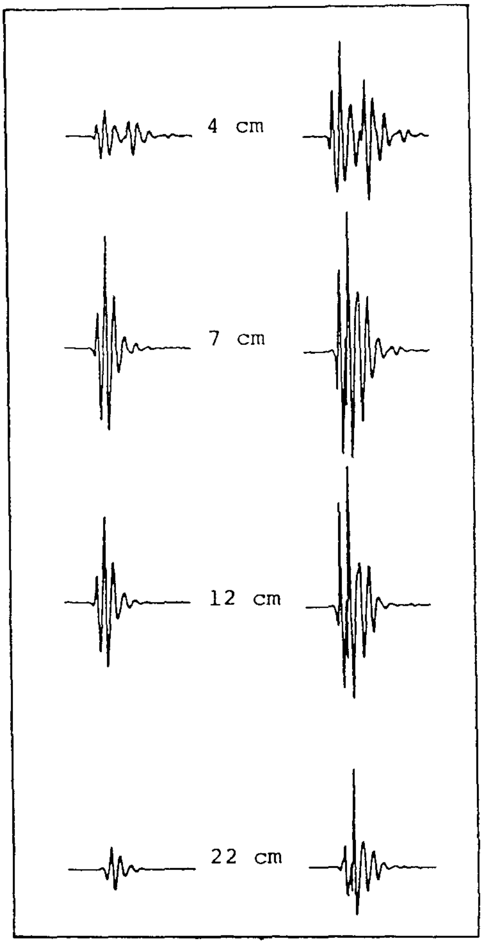



Fig. 6. Axial pulse shapes as measured by a point (0.5 mm diameter) hydrophone at different distances from a focused (nominally 9 cm) transducer for linear (left-hand column) and nonlinear (right-hand column) propagation in water. An unchanging receiver amplifier gain was used for all the linear field results, which are displayed to the same scale. Similarly, for the nonlinear results, an unchanging receiver amplifier gain was used, except that its value was reduced, in order to compensate for thé increased outgoing pulse intensity.

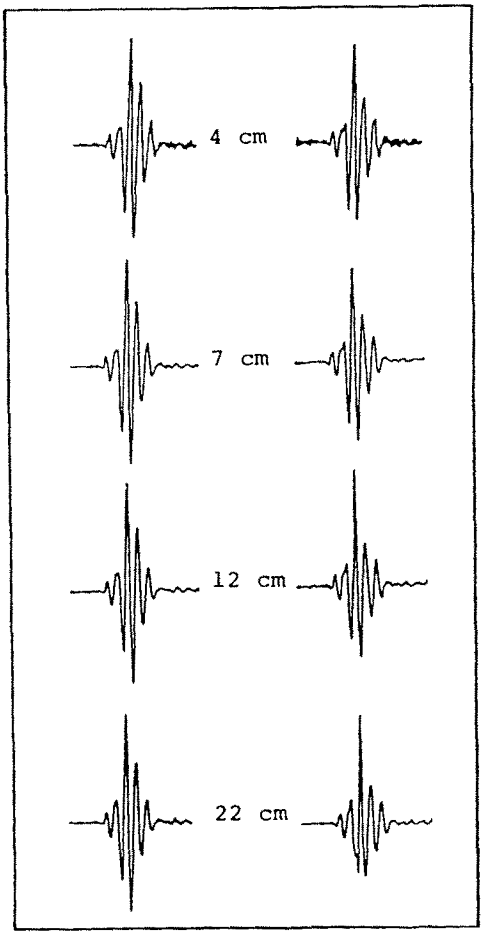



Fig. 7. Pulse shapes as measured with a diffraction-free hydrophone for the same distances from the same focused transducer (nominal focus at 9 cm) for linear (left-hand column) and nonlinear (right-hand column) propagation in water, as in figure 6. An unchanging receiver amplifier gain was used for all the linear field results, which are displayed to the same scale. Similarly, for the nonlinear results, an unchanging receiver amplifier gain was used, except that its value was reduced, in order to compensate for the increased outgoing pulse intensity.

diffraction effects intruding, thus allowing the study of this effect without the need for focusing and diffraction corrections.

## CONCLUSION

We have demonstrated the possibility of constructing a diffraction-free hydrophone that functioned in accord with theoretical predictions, and have shown its applications to measurement of attenuation and characteristic impedance (for the linear case), and we note a clear role for the diffraction-free hydrophone in the study of nonlinear propagation, reducing the complications introduced by diffraction when measuring acoustic parameters in nonlinear fields.

## ACKNOWLEDGEMENTS

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SUPERANDO O ARTEFATO DE DIFRAÇÃO ULTRA-SÔNICA
II. ESTIMATIVA DE ATENUAÇÃO, IMPEDÂNCIA CARACTERISTICA
E PROPAGAÇÃO NÃO LINEAR

RESUMO--É mostrado que um hidrofone especialmente construído pode ser utilizado com campos ultra-sônicos pulsáteis para a realização de medidas livres de artefatos da atenuação, impedância característica e efeitos não lineares. A tecnologia garante que artefatos de difração são minimizados nas medições.