# OVERCOMING THE ULTRASOUND DIFFRACTION ARTEFACT
# I. THEORY AND EXPERIMENTAL VERIFICATION

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ABSTRACT -- A new approach towards measuring ultrasound fields and pulses, which is insensitive to diffraction artefacts, is described. The theoretical justification for the technique is shown to be valid, on the basis of experiments conducted with a purpose-built hydrophone.

## INTRODUCTION

The transient pressure field produced by a piston-like transducer has been described as a sum of two major components (Weight and Hayman, 1978): "direct" and "edge" waves. However, the first experimental verification of this for the medical ultrasound case was achieved in the context of the "replica pulse" formulation of Freedman (1961) by Gore and Leeman (1977). The edge waves are produced by the periphery of the transducer and are the cause of the diffraction effects observed in many measurement and calibration schemes based on techniques using small hydrophones to probe ultrasound fields.

Many techniques have hitherto been proposed to overcome these diffraction effects, generally based on computational methods for diffraction correction (Fink and Hottier, 1982). Another alternative is to perform measurements only in the far field of the transducers: on occasions, this demands the use of unwieldy and cumbersomely large water tanks.

We present here the theoretical basis of a novel technique for minimizing measurement artefacts arising from diffraction. This technique is based upon a purpose-built PVDF hydrophone which allows equivalent one-dimensional measurements to be made of real, three-dimensional pulsed fields.

## THEORY

The main points of the theory are more clearly demonstrated in a simple example. Consider a one-dimensional (1-D) pulse $p(x,t)$ propagating linearly in an ideal, lossless, uniform medium. This pulse can be written as a solution of the 1-D wave equation for example, such that:

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$$\frac{\partial^2}{\partial x^2}\, p(x,t) - \frac{1}{c^2}\,\frac{\partial^2}{\partial t^2}\, p(x,t) = 0 \tag{1}$$

where: x = space coordinate
t = time coordinate
c = (constant) velocity of sound in that medium.

We consider only the case of a forward travelling pulse, i.e. p(x,t) is equal to p(x-ct).

The representation of p(x-ct) in the Fourier domain can be written as:

$$p(x-ct) = \frac{1}{2\pi} \int P(\omega)\, e^{i(\omega t - kx)}\, d\omega \tag{2}$$

with: $k = \omega/c$
$P(\omega)$ = Fourier Transform (FT) of p(x-ct)

The 1-D pulse does not change its form or amplitude as it propagates, i.e. it does not show diffraction effects.

A three-dimensional (3-D) pulse p(x,y,z;t) [= $p(\underline{r},t)$] propagating linearly in the same ideal, lossless, uniform medium must satisfy the 3-D wave equation:

$$\nabla^2 p(\underline{r},t) - \frac{1}{c^2}\,\frac{\partial^2}{\partial t^2}\, p(\underline{r},t) = 0 \tag{3}$$

The equivalent representation of $p(\underline{r},t)$ in the Fourier domain is written as:

$$p(\underline{r},t) = \frac{1}{(2\pi)^3} \int d^3\underline{k}\; P(\underline{k})\; e^{i(\omega t - \underline{k}\cdot\underline{r})} \tag{4}$$

where: $\omega = c|k| = ck = c(k_x^2 + k_y^2 + k_z^2)^{\frac{1}{2}}$

$\underline{k}$ = wave vector associated with the plane wave component of wavelength $\lambda$ ($=2\pi/k$) and direction $\underline{n}$, where $\underline{k} = \underline{n}k$
$P(\underline{k}) = P(k_x,k_y,k_z)$

Consider a hypothetical, ideal, infinitely extended and coherently detecting planar hydrophone, located at $x_o$ and intercepting this 3-D pulse orthogonally to its propagating (x-) direction. The output of such a device can be expressed as:

$$p_{df}(x_o,t) = \int dy \int dz\;\; p(x_o,y,z,t) \tag{5}$$

which can be written as:

$$p_{df}(x_o,t) = \frac{1}{(2\pi)^3} \int dy \int dz \left[ \int dk_x \int dk_y \int dk_z\; P(k_x,k_y,k_z)\; e^{i(\omega t - k_x x_o - k_y y - k_z z)} \right] \tag{6}$$

Using the representation $\delta(q) = 1/2\pi \int e^{ipq}dp$, and integrating over the variables $k_y$ and $k_z$, gives:

$$p_{df}(x_o,t) = \frac{1}{2\pi} \int dk_x \, P(k_x,0,0) \, e^{i(\omega t - k_x x_o)}$$

$$= \frac{1}{2\pi} \int dk \, F(k) \, e^{i(\omega t - kx_o)} \qquad (7)$$

where: $\omega = ck$
$F(k) = P(k,0,0)$

Eq.(7) shows that $p_{df}(x_o,t)$ is an equivalent, "true" 1-D pulse with Fourier Transform $F(k)$, that is invariant in shape and independent of location $x_o$, thus being free from diffraction artefacts. The spectrum of the output (1-D) pulse is identically equal to the values taken on by the three-dimensional pulse spectrum, along a line oriented in Fourier space in the same direction as the orthogonal to the hydrophone plane [see eqn.(7)]. The validity of this statement depends only on the ability to express the original field as a superposition of travelling plane waves, and does not require the field itself to have planar wavefronts. For example, even a spherically converging wavefront, as in a focused field, can be expressed as a superposition of plane waves, and, even in this case, the large planar hydrophone will give a distance invariant output as it moves through the focus, as experimentally confirmed below.

## EXPERIMENTAL VERIFICATION

The ideal hydrophone (infinitely large and planar) is obviously impossible to construct, but can be substituted by a planar transducer sufficiently large to effectively intercept the entire propagating pulse $p(\underline{r},t)$.

We have constructed a large planar receiver from stretched 25 µm PVDF film, with a circular active surface of 75mm diameter. This approximates to the large, planar, coherent receiver required by our technique. The constructed hydrophone was large enough to intercept the entire propagating pulse produced by a 24 mm diameter planar, unbacked, 1.5 MHz PZT transducer, and the results obtained at three different locations within the nominal near and far field are shown in figure 1.

Comparison of these results with those in figure 2, obtained with a point hydrophone (0.5 mm diameter, Marconi bilaminar shielded), in the same pulsed field and at the same (axial) locations, amply justify the statements of the previous sections. Note that the large receiver outputs, as predicted, a remarkably invariant pulse, with no significant change in shape and in amplitude over the entire 30 cm range of measurement locations possible in our water tank. On the contrary, for the point hydrophone, notably in the near field, diffraction effects are clearly visible.

As has been pointed out in the previous section, the proposed technique is, in fact, generally valid even when measuring the output from a focused transducer. The diffraction-free hydrophone was used to probe the ultrasound field produced by a 2.25 MHz, 19mm diameter, 9 cm focused transducer and we compared the results obtained (see figure 3) at three different locations in this pulsed field with those obtained with the point hydrophone above described (see figure 4). We see that, as expected, the received signal using the point hydrophone varies in its shape and in

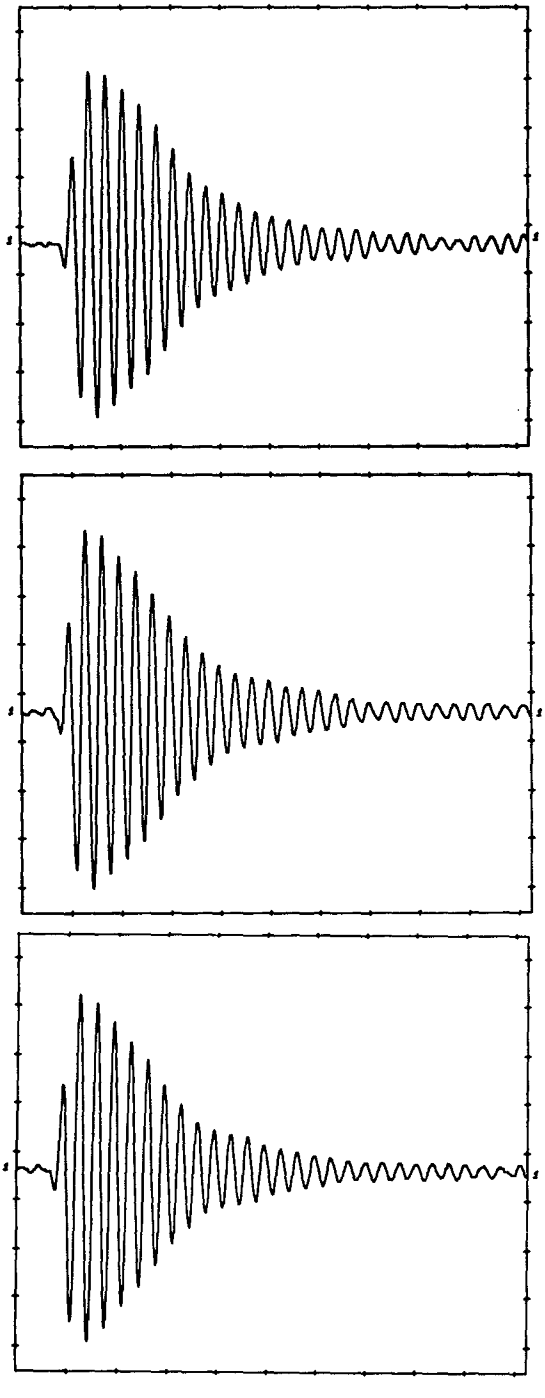

Fig. 1. Output waveforms from a large PVDF hydrophone (as described in text) at three different locations in the transient field produced by a planar, unbacked 24 mm diameter 1.5 MHz PZT transducer. Received pulses for on-axis locations at 2 cm (top), 17 cm (centre) and 31 cm (bottom) from the transmitter are shown. Amplitude and time scales are identical for all three cases.

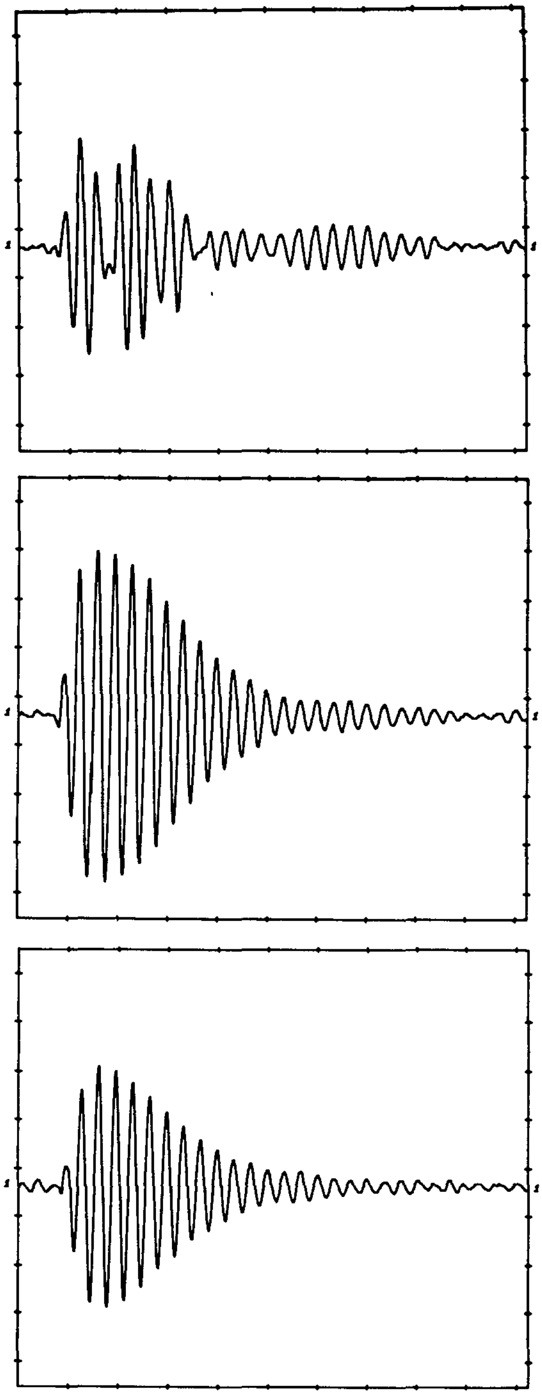

Fig. 2. Output waveforms of a "point" hydrophone (0.5 mm diameter) located at the same locations, in the same field, as the diffraction-free hydrophone in figure 1. Amplitude and time scales are identical in all three cases.

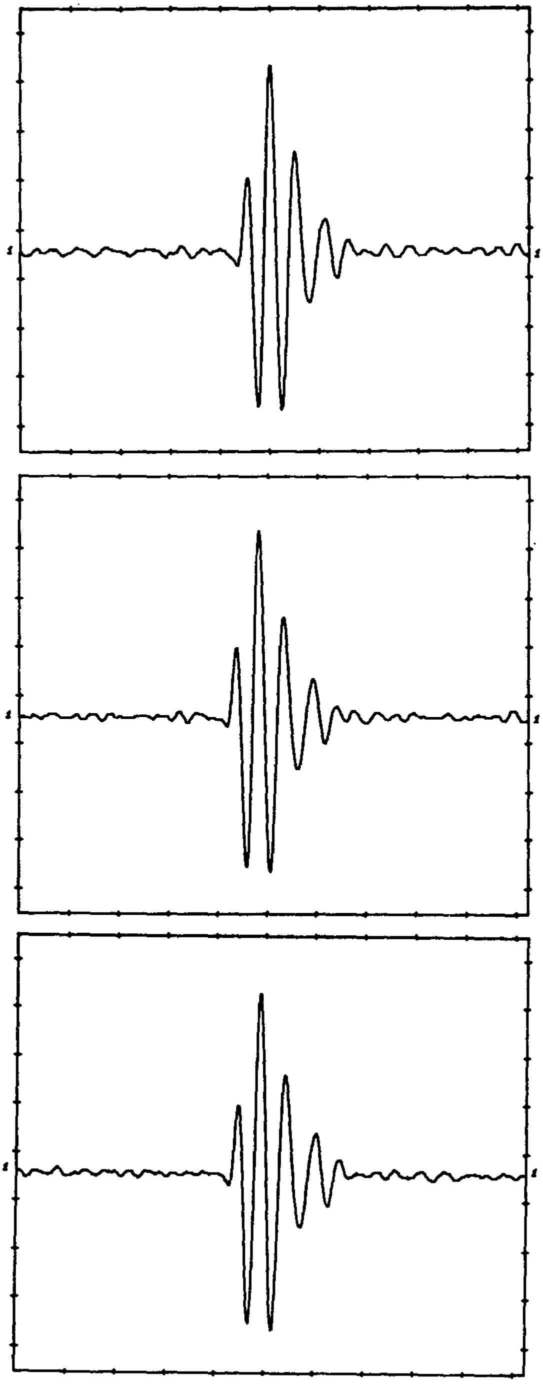

Fig. 3. Output from the purpose built diffraction-free hydrophone at three different locations (on axis) of a pulsed ultrasound field generated by a 19 mm diameter, 2.25 MHz (nominal), focused transducer. Amplitude and time scales are identical in all three cases. Top: at 3 cm from the transmitter (before focus); centre: at 9 cm from the transmitter (nominal focus); bottom: at 20 cm from the transmitter (beyond focus).

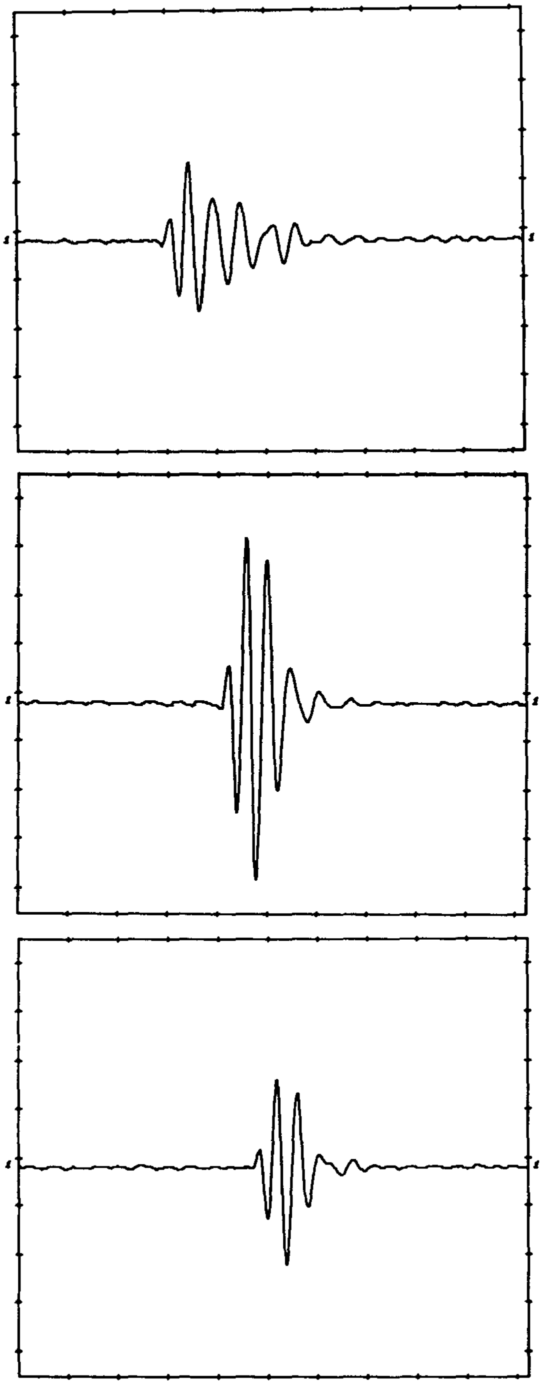

Fig. 4. Output from a "point" hydrophone (0.5 mm diameter) at the same locations and in the same field as explained in figure 3. As before, amplitudes and time scales are identical in all three cases.

amplitude, according to the position in the field. The purpose-built hydrophone, on the contrary, gives a remarkably invariant pulse (in shape and in amplitude), even when located at the nominal focus of the transmitter.

## CONCLUSION

We have presented a new approach towards the diffraction-free measurement of 3-D pulses, and have shown the practical feasibility of the technique. The results presented here have indicated, and demonstrated the power of, the method, and give direct experimental support to an apparently idealised and theoretical concept. As pointed out by Leeman et al (1985), the technique is particularly useful for diffraction-free attenuation measurements, and its wider utility for field calibration and output measurements, is immediately apparent. In a following paper (Costa et al, 1987) we show several applications of the "diffraction free" hydrophone in measuring pulsed ultrasound fields.

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SUPERANDO O ARTEFATO DE DIFRAÇÃO ULTRA-SÔNICA
I. TEORIA E VERIFICAÇÃO EXPERIMENTAL

RESUMO--Uma nova aproximação para a medição de campos acústicos e pulsos, que é insensitiva a artefatos de difração, é descrita. A justificativa teórica para a técnica é demonstrada válida com base em experiências conduzidas com um hidrofone especialmente construído para este fim.