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MEASUREMENT AND CALIBRATION OF TRANSDUCER FIELDS

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INTRODUCTION

Pulsed fields from real transducers are very different to the idealised one-dimensional (1-D) entities that form the basis for many measurement and calibration schemes. In general, small hydrophones approximating to an ideal point probe are used to detect the acoustic signal emitted by a transducer. A picture of the transient field is built up by scanning the hydrophone in a plane perpendicular to the direction of the travelling pulse as well as by translating it along the transducer axis. As we can see in fig.1, the measured pulse changes in shape with hydrophone position, making it impossible to talk of the emitted pulse.

It is important to measure pulses accurately for at least three purposes: 1) signal processing; 2) attenuation estimation; and 3) field calibration and output measurements. The question therefore arises as to which, if any, hydrophone measurement is most suitable for these purposes. What is needed is to define a meaningful pulse measurement technique which gives unique and characteristic information about the emitted pulse itself, independently of hydrophone location.

The aim of this work is to show a new technique whereby equivalent 1-D measurements may be made of real, three-dimensional (3-D) pulsed fields. A specially designed hydrophone has been constructed and measurements made with it illustrate its practical advantages.

WHAT IS A GOOD MEASUREMENT?

An ultrasound pulse is a single entity and by its very nature is a function of time. A "good" measurement of that pulse may clearly result in a function of time, but should be an intrinsic property, independent of location in the field. Thus what we are looking for are invariant pulse features such as, in another context, would be represented by the energy of that pulse (assuming a linear lossless propagation medium). These tentative remarks are illustrated and clarified in the following examples.

The one-dimensional pulse

Consider a 1-D pulse propagating linearly in an ideal, lossless, uniform medium for which the wave equation is

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

Here x and t are the space and time coordinates respectively, p is the pressure and c is the (constant) velocity of sound in that medium. A general solution to (1) is given by

$$p(x,t) = Ap(x-ct) + Bp(x+ct) \qquad (2)$$

and, for a forward travelling pulse, the initial condition B = 0 is chosen so that (2) reduces to

$$p(x,t) = Ap(x-ct) \qquad (3)$$

This represents a pulse propagating with constant velocity c in the positive x-direction and with shape independent of location. For example, by our definition, the time of arrival of the pulse is not a good measurement since it is location and in fact medium (velocity) dependent. On the other hand, the peak amplitude of the pulse _is_ a good measurement since it is a characteristic feature of the pulse, not changing with its location.

Equivalent representations for the pulse can be written in either the time or frequency domains, via its Fourier transform (F.T.):

$$p(x-ct) = \frac{1}{2\pi}\int_{-\infty}^{\infty} P(w)\exp[i(wt-kx)]dw \qquad (4)$$

with $w = ck$, k the wavenumber ($k = 2\pi/\lambda$), and P(w) the Fourier transform of p (x,t). It is important to notice that P(w) is a characteristic feature of the pulse, and does not depend on location nor on time. A good measurement of the ideal 1-D pulse, in the w-domain, would be to measure either P(w) itself, or some of its characteristic features.

The three-dimensional pulse

Consider now a real 3-D pulse propagating in an ideal, lossless, uniform medium, assuming again the validity of linearity. The wave equation can be written as

$$\nabla^2 p(\underline{r},t) - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} p(\underline{r},t) = 0 \qquad (5)$$

where: $\nabla^2 = \frac{\partial^2}{\partial x^2}[\ ] + \frac{\partial^2}{\partial y^2}[\ ] + \frac{\partial^2}{\partial z^2}[\ ]$

$\underline{r} = (x,y,z)$

c = characteristic of the medium

A pulse solution of (5), $p(\underline{r},t)$, can be related (as in the 1-D case) to its F.T. according to

$$p(\underline{r},t) = \frac{1}{(2\pi)^3}\int_{-\infty}^{\infty} d^3\underline{k}\ P(\underline{k})\exp[i(wt-\underline{k}.\underline{r})] \quad (6)$$

with: $w=c|\underline{k}|= c(k_x^2+k_y^2+k_z^2)^{\frac{1}{2}}$
k = wave vector associated with the wave component of wavelength $2\pi/k$ and direction $\underline{n}$, with $\underline{k} = \underline{n}k$
$P(\underline{k})$= F.T. of $p(\underline{r},t)$

$P(\underline{k})$ and $p(\underline{r},t)$ are equivalent representations for the pulse, one in the time domain and the other in k-space. $P(\underline{k})$ is a characteristic feature of the pulse and it is important to notice that it does not depend on location ($\underline{r}$) or on time (t). Once again, a good measurement of the real 3-D pulse would be to measure $P(\underline{k})$ or, at least, some of its characteristic features.

How to measure P(k)

Consider the output of a hypothetical, ideal, infinitely extended and coherently detecting planar hydrophone located at x_o, orthogonally intercepting a 3-D pulse propagating in the x-direction. The output of such measuring device is mathematically expressed by

$$p_{DF}(x_o,t) = \int_{-\infty}^{\infty}dy\int_{-\infty}^{\infty}dz[p(x_o,y,z;t)] \quad (7)$$

The equivalent representation in the $\underline{k}$-space for (7) is given by

$$p_{DF}(x_o,t) = \frac{1}{(2\pi)^3}\int_{-\infty}^{\infty}dy\int_{-\infty}^{\infty}dz[\int_{-\infty}^{\infty}dk_x\int_{-\infty}^{\infty}dk_y\int_{-\infty}^{\infty}dk_z\ P(k_x,k_y,k_z)\exp[i(wt-k_xx-k_yy-k_zz)]] \quad (8)$$

But we know that

$$\delta(q)= \frac{1}{2\pi}\int_{-\infty}^{\infty}\exp(ipq)dp \quad (9)$$

Using equation (9) and developing equation (8) for the space variables y and z we have

$$p_{DF}(x_o,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty}dk_x\int_{-\infty}^{\infty}dk_y\int_{-\infty}^{\infty}dk_z\ P(k_x,k_y,k_z)\exp[i(wt-k_xx)]\delta(k_y)\,\delta(k_z)$$

$$p_{DF}(x_o,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty}dk_x\ P(k_x,0,0)\exp[i(wt-k_xx_o)]$$

$$p_{DF}(x_o,t)= \frac{1}{2\pi}\int_{-\infty}^{\infty}dk\ \mathbb{P}(k)\exp[i(wt-kx_o)] \quad (10)$$

We can see from equation (10) that $p_{DF}(x_o,t)$ is a one-dimensional pulse with Fourier transform $\mathbb{P}(k)$ that is invariant in shape and independent of location (x_o). We can also see that $p_{df}(x,t)$, i.e. the pulse measured at arbitrary location x, can be written as a solution to the wave equation (1), that is

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

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 can substantiate this statement by direct measurement of pulsed fields with planar commercial and specially-constructed receivers.

EXPERIMENTAL VERIFICATION

We have constructed a large receiver from stretched 110µm, PVDF film, with a circular active surface of 75mm diameter. This approximates to the large, planar, coherent receiver required by our technique. The constructed receiver was large enough to intercept the entire propagating pulse produced by a 24mm diameter planar, unbacked, 3MHz PZT transducer, and the results obtained at three different locations within the nominal near field are shown in fig.2.

Comparison of these results with those in fig.1 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 or amplitude over the entire 30cm range of measurement locations possible in our water tank.

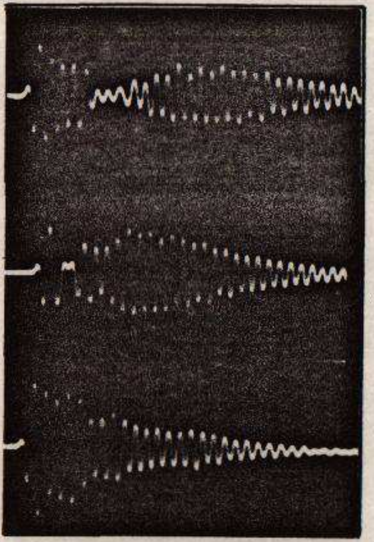
We should emphasize that the proposed technique is, in fact, generally valid when measuring the output from a focused transducer. To emphasize that the receiver need not necessarily be "infinite" in size, but need only intercept the lateral extent of the measured field, we performed experiments with a standard, planar PZT receiver slightly smaller diameter than a focused transmitter. The transmitting transducer (KB-AEROTECH 3.5MHz) had an aperture of 13mm diameter and was focused at 7cm. The receiving transducer was a planar PZT transducer of 10mm diameter and the results obtained are shown in fig.3, which are the monitored on-axis waveforms at various distances from the transmitter. In this experiment, the output of the receiver was digitized at 20MHz rate, to 8-bit accuracy, before display. Small differences in the waveforms 3(a) - 3(c) may be ascribed entirely to digitization errors.

CONCLUSIONS

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 vindicated, 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.[1], the technique is particularly useful for diffraction-free attenuation measurements, and its wider utility for field calibration and output measurements, is immediately apparent.

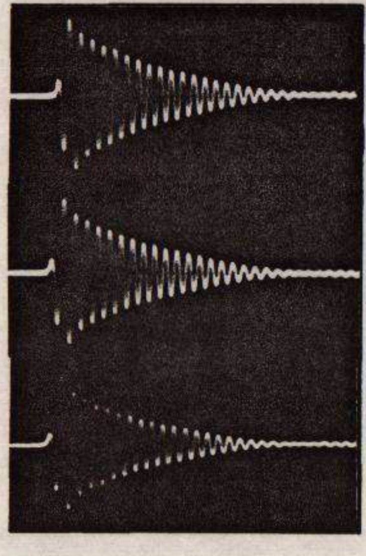
REFERENCES

[1] Leeman S., D.Seggie, L.A.Ferrari, P.V.Sankar and M.Doherty, 'Diffraction-free atten uation estimation', Proceedings of Ultrasonics International 85, 128-132, Butterworth Scientific Ltd., Guildford, (1985).



a b c

Fig.1. Output waveforms of a small hydrophone at three different locations in the transient ultrasound field produced by a planar, unbacked 24mm diameter, 3MHz PZT disc. Received pulses for on-axis locations at distances (a) 7.5cm, (b)15cm, and (c)30cm from the transmitter are shown.



a b c

Fig.2 Output waveforms obtained with a large PVDF hydrophone (as described in text) located at the same positions, in the same field, as the small hydrophone in fig.1. Amplitude and time-scale are identical in all three cases.

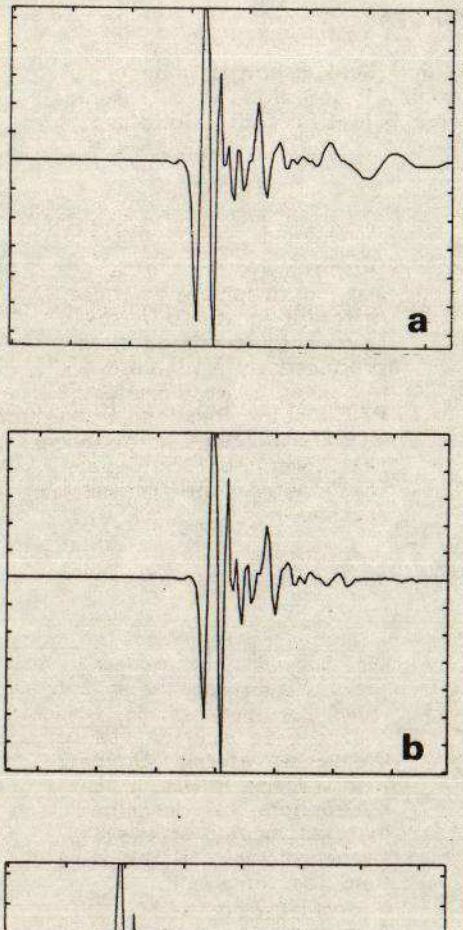


Fig.3 Output waveforms from a backed, planar 10mm diameter receiver, located on-axis, at distances (a) 1cm, (b) 3cm and (c) 6cm from an internally focused, backed transmitter (KB-AEROTECH 3.5MHz, 13mm diameter, 7cm focus).