A novel sensor for determining ultrasonic intensity

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***Abstract*— Quantifying the acoustic output of diagnostic and therapeutic medical ultrasound devices is an established practice, using measurement methods based on applying miniature hydrophones to determine acoustic pressure distributions. However, specification standards require manufacturers to describe and declare acoustic output information in the form of intensity values, as these are more relevant to the possibility of adverse bioeffects. Simple relationships exist to calculate intensities from pressure data, but under many circumstances, such as away from the acoustic axis and in the transducer near-field, the underpinning assumptions break down.**

This paper describes the design, development and testing to proof-of-concept of a novel design of ultrasound sensor which can determine intensity directly. The sensor uses the *pyroelectric* properties of the *piezoelectric* polymer PVDF, and takes the form of a conventional membrane hydrophone backed with a highly attenuating polyurethane-based material. Ultrasound incident on the backing material is quickly absorbed, and the rate of temperature increase over a short timescale is proportional to the intensity in the beam, and produces a pyroelectric voltage response in the PVDF film. The new sensor also behaves as a conventional hydrophone, and can be used to derive acoustic pressure profiles. Intensity results are compared with pressure-squared data obtained from beam-plotting a range of simple transducer fields, and suggest differences in the beam profiles, particularly in the acoustic near field.

Keywords; ultrasound, measurement, pressure, intensity, exposure, safety

I. Introduction

To market and sell medical ultrasound devices, manufacturers must comply with specification standards describing methods for determining and declaring parameter values of, and limitations in, acoustic output [1], [2], [3], [4]. Procedures are well established, and describe the use of calibrated piezoelectric hydrophones to make measurements of acoustic pressure [5]. Yet the majority of safety-related acoustic output parameters [6] are described in terms of intensities, as these have been shown to relate more closely to bioeffects [7].

Intensity itself may be defined as the acoustic flux density, is a vector quantity, and is calculated from the product of the particle velocity, *u*, and the acoustic pressure, *p*. In practical terms, only the latter may be measured readily, and given the relationships between the parameters for plane-progressive waves, where the scalar quantities are considered:

$$p = \rho \, c \, u \tag{1}$$

$$u = p \, / \, \rho \, c \tag{2}$$

where ρ and c are the mass density and speed of sound respectively, the familiar relation for intensity, I, results:

$$I = p^2 / \rho \, c \tag{3}$$

For declaring parameters, calculations of intensities from pressures are carried out under assumptions of plane wave behaviour [8], and in most cases, these assumptions are valid. However, there are situations where they break down, such as in the acoustic near field. Some specification standards limit the proximity to the transducer output face at which measurements may be made [4], but there are situations in which data must be acquired very close to the source [9]. So, to eliminate uncertainties in converting acoustic pressure values, and to provide a direct measurement of intensity for underpinning ultrasound safety standards, an intensity measurement device is highly desirable.

II. Experimental: Devices and Set-up

A. Measurement sensor

Recent research at NPL has developed a measurement technique for determining acoustic power, based on utilising the *pyroelectric* effect of a thin film of the *piezoelectric* polymer polyvinylidene fluoride, PVDF [10, 11]. The method, shown schematically in Figure 1, uses a large area sensor to capture the incident acoustical energy absorbed in a very thin layer of a highly attenuating back layer in intimate contact with the detecting film, and under certain conditions the maximum change in the pyroelectric voltage induced immediately after the ultrasonic source is switched on or off is proportional to the ultrasonic power contained in the beam.

In this paper, this technique is extended to a similar sensor concept, but deployed over a small area, which is hypothesized would result in the time-averaged power over a small region of the incident beam being measured, i.e. a time-averaged intensity measurement.

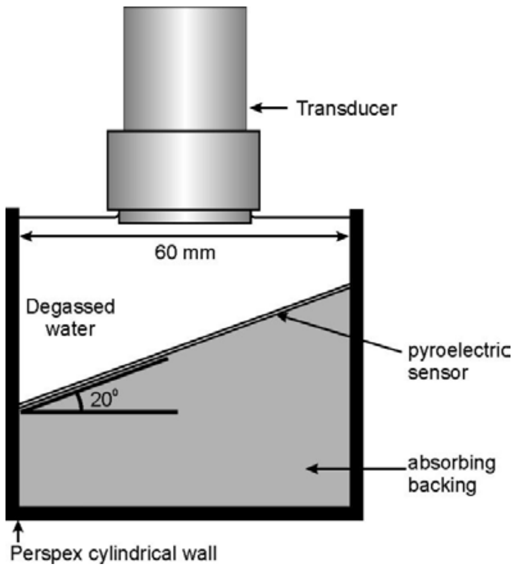

Figure 1. Schematic representation of the pyroelectric power measurement concept. The schematic shows a device developed for measuring therapeutic fields which tend to operate in CW or quasi-CW excitations: the sensor is thus tilted to eliminate reflections

To realize the sensor prototype, a conventional piezoelectric hydrophone was backed with a 10 mm thick layer of a proprietary acoustical absorber (Figure 2), providing a one-way transmission loss of 107 dB cm^{-1} at 1 MHz.

Figure 2. Intensity sensor prototype (ISP)

In this way, the incident sound at low megahertz frequencies is absorbed in a material layer of a mm or so close to the sensor film, and the resulting temperature rise is quickly transferred to it. The poled central region of the hydrophone has an active element of nominal diameter 0.4 mm, which defines the spatial resolution of the device. In addition to being a pyroelectric sensor, the hydrophone also retains its piezoelectric characteristics, and so can be used to carry out measurements of both intensity and pressure, depending on the electronics to which it is connected.

B. Electronics

To make measurements, the intensity sensor prototype (ISP) was connected to either a Tektronix TDS 784D oscilloscope (Tektronix UK Ltd., Berks, UK) for acoustic pressure measurements, or to bespoke electronics for intensity measurements, as described in detail in Zeqiri et al [10]. The circuitry consists of an initial low-pass filter, with a -20 dB roll-off at 27 Hz, and a subsequent variable gain stage. Output signals were then acquired using a Tektronix TDS 7104 oscilloscope (Tektronix UK Ltd., Berks., UK). In both cases, the respective oscilloscopes were operated under PC control.

C. Acoustic fields

Single-element focused and plane-piston Panametrics 3.5 MHz transducers were used, of 13 mm and 19 mm diameters respectively; the acoustic output of which had been characterized previously using beam plotting facilities at NPL. The transducers were driven by an Agilent 33250A function generator (Agilent Technologies Ltd, Berks., UK) through an AR 150A100B RF power amplifier (AR, Bucks., UK). Excitation conditions for both transducers were chosen to generate spatial-peak-temporal-average intensities (I_{spta}) values of around 100 - 500 mW cm^{-2}, typical of diagnostic scanners, but limiting the extent of nonlinear propagation in the water paths used.

III. EXPERIMENTAL: RESULTS

A. Typical ISP waveforms

An example of a waveform received from the ISP, and measured using the TDS 7104 oscilloscope is shown in Figure 3. It illustrates a typical measurement protocol, in which the sensor was moved under motor control to the acoustic field location of interest, in this case the focus of the 3.5 MHz focused transducer, producing an I_{spta} of around 500 mW cm^{-2}, with the sensor then being left to settle for three seconds. The transducer was then energized, and switched off again after a further 3 seconds. The impedance of the bespoke electronics is designed such that the sensor responds to the *rate of change* of temperature [10], and so the sharp rise and fall in the measured waveform corresponds to the rapid heating and cooling of the PVDF element immediately after the transducer is switched on and off respectively.

The inset graph shows the sharpness of the transition: the maximum rate of temperature rise occurs around 60 ms after switch-on, and diminishes beyond this due to heat conduction away from the sensor/backing interface. In practice, the maximal changes in voltage are measured, and an average taken as the pyroelectric voltage corresponding to the I_{spta} at the field location under test. For scanning measurements, a delay time of at least 30 seconds was allowed between measurements, to allow the sensor to cool, and minimize any adverse effects of thermal damage, or of the acoustical properties of the material changing with temperature and altering the device sensitivity.

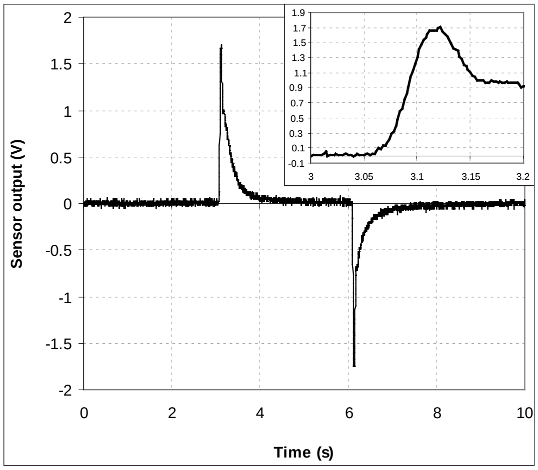

Figure 3. Example waveform from intensity sensor, at the focus of a 3.5 MHz focused transducer. The inset graph shows an expanded of the sharp rise time.

B. *Comparison of sensor beam profiles*

As discussed above, the ISP retains its characteristic as a conventional hydrophone, and so comparison measurements were made using the ISP in both measurement configurations, and with a second hydrophone, an Onda HGL0085 device (Onda Corp., Sunnyvale, CA). Beam profiles, plotted across the alignment axis at the last axial maximum of a 3.5 MHz plane transducer are shown in Figure 4, for the three measurement configurations. To eliminate standing waves set up between the transducer and the ISP (operating both as an intensity sensor and as a hydrophone) necessitated tilting it by 4 degrees about the receiving element.

The pressure measurements made with the GL0085 hydrophone are shown as the black diamonds; the ISP pressure measurements as the open triangles, and the ISP intensity measurements as the grey squares. For the pressure measurement sets, the measured values have been squared, and each set normalized, for comparison purposes. On the acoustic axis, and out to around ±2 mm, all three configurations agree well, but beyond this, the ISP intensity variation appears to fall away more quickly.

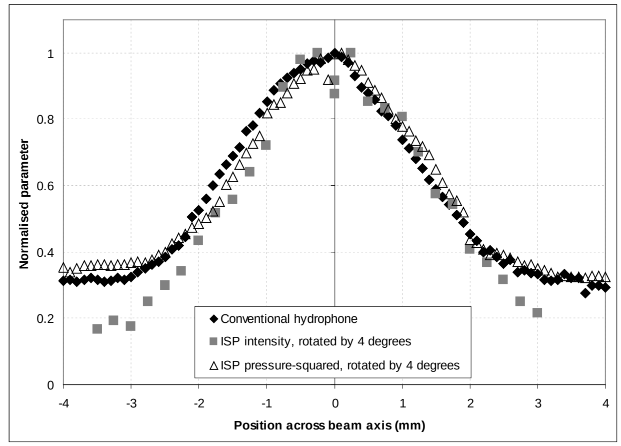

Figure 4. Comparison of three cross-axial beam profile measurements carried out at the last-axial maximum of a 3.5 MHz plane transducer

This may be a genuine difference in the measured quantities, or a measurement artifact, and is currently under investigation. The agreement between the ISP pressure-squared data and the conventional hydrophone is very good, showing the continued performance of the ISP as a conventional pressure hydrophone and so for subsequent studies, the ISP was used in both configurations without separate comparison.

Figure 5 shows a cross-axial scan carried out at the last-axial minimum of the 3.5 MHz focused transducer, with a comparison shown of pressure-squared (from ISP hydrophone measurements) and normalized I_{spta} (from ISP intensity measurements). The profiles agree quite well, although the more significant differences occur again at the edges of the distribution, and close to the acoustic axis. This may be indicating differences between the conventional, pressure-squared technique and the direct intensity measurement approach, perhaps due to the acoustic pressure and particle velocity not being in phase as assumed in the pressure to intensity conversion.

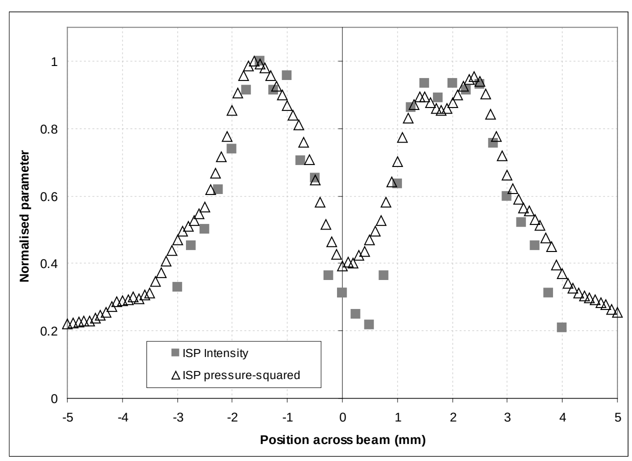

Figure 5. Comparison of two cross-axial beam profile measurements carried out at the last-axial minimum of a 3.5 MHz focused transducer

The final result, shown in Figure 6, shows the variation in pressure-squared and intensity as a function of angle, for the

ISP located at the last-axial maximum of the 3.5 MHz plane transducer.

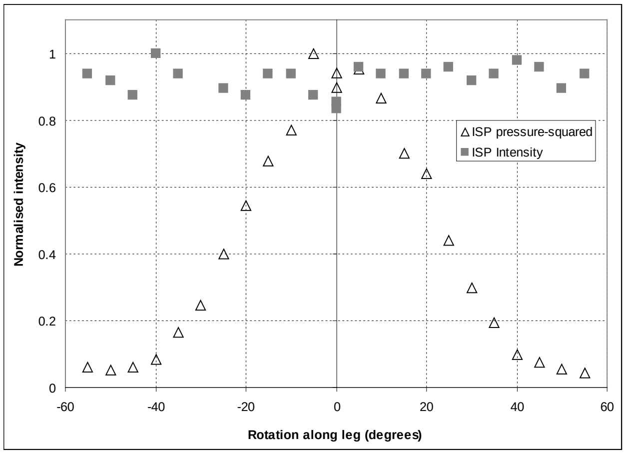

Figure 6. Comparison of angular variations in pressure-squared and Ispta, determined using the ISP

This shows the expected, and predictable response in the pressure-squared profile, representative of the hydrophone acting as a stiff-disc receiver, and demonstrating a first-order Bessel function fall-off of around -6 dB for a rotation angle of 25 degrees. By contrast, the intensity response appears to show very little variation in measured value with the rotational angle. Conceptually, this might be expected: as for the intensity sensor, the volume of the absorbing material which is exposed to the incident beam remains constant as the sensor is rotated relative to the beam, and hence the resulting heating effect does not change. However, a theoretical model would be needed to confirm this.

IV. CONCLUSIONS

The introductory studies shown here have demonstrated the extension of the previously demonstrated pyroelectric sensor large area power measurement concept to a small-area, local time-averaged intensity sensor. This has been achieved through depositing a highly attenuating backing layer onto a conventional spot-poled 0.4 mm active element diameter membrane hydrophone, and has resulted in an Intensity Sensor Prototype (ISP) which retains its piezoelectric characteristics, but which can also exploit the pyroelectric properties of PVDF.

Early results obtained with the device have shown that as a hydrophone, it produces beam profiles that agree well with a conventional hydrophone. Yet as an intensity sensor, subtle differences are seen in the acoustic near field and away from the beam axis. These remain the subject of ongoing investigation, but may arise from breakdowns in the fundamental assumptions of the acoustic pressure and particle velocity being in phase, which underpins the present state of the art in ultrasonic exposimetry. This may have implications for beam characterization, such as for therapeutic fields, in which measurements are required to be carried out in the acoustic near field close to the transducer face.

The present non-optimised configuration is able to measure I_{spta} values as low as 25 mW cm^{-2}, and so with improvements to the noise performance, the device sensitivity would be sufficient to characterize a wide range of diagnostic ultrasound devices.

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