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THE ABSOLUTE CALIBRATION OF HYDROPHONES AND THEIR USE IN THE MEASUREMENT OF THE OUTPUT FROM MEDICAL ULTRASONIC EQUIPMENT

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Introduction

The present dramatic increase in the use of ultrasound in hospitals is resulting in a significant proportion of the population of this country being exposed to ultrasonic radiation, and with this increase has come a requirement for the determination of the output from medical ultrasonic equipment. The most widely used and convenient method of measuring the spatial and temporal characteristics of ultrasonic fields is by means of miniature hydrophones. These hydrophones are not absolute devices and the relation between the voltage they produce and the applied pressure in the ultrasonic field must be determined by calibration. Two particular techniques for hydrophone calibration, total power combined with beam plotting, and reciprocity, are commonly used and are being studied at the National Physical Laboratory (NPL).

Hydrophone calibration by total power combined with beam plotting

In the total power combined with beam plotting technique, the total power from a transducer is measured using a radiation pressure balance and compared with a value obtained by scanning a hydrophone over the field and integrating. The output power from the transducer is measured in the radiation pressure balance at different applied voltages, under continuous excitation, giving a determination of output power/volt^2. The transducer is then transferred to a beam plotting tank and the hydrophone to be calibrated is moved horizontally throughout the field across a line perpendicular to the direction of the ultrasonic beam. With tone-burst excitation of the transducer, the received signal at the hydrophone is measured as a function of the position of the hydrophone in the beam, producing a beam scan in one direction. The transducer is then rotated about its acoustic axis through an angle of 90° and another horizontal beam scan obtained. From the known excitation voltage for the tone burst, the equivalent continuous mode output power of the transducer can be derived using the radiation pressure calibration. If various assumptions are made, these two scans can be integrated and, after dividing by this total power, a value for the sensitivity of the hydrophone can be derived.

Although this technique appears simple, there are a number of possible sources of uncertainty. Firstly, the scanning is only performed along two perpendicular axes and to obtain an integral over the whole beam, some assumption of field symmetry must be made. A raster scan over the whole beam is preferable, but this would be very time-consuming. Two other major sources of uncertainty in this technique arise from the hydrophone itself. Firstly, the hydrophone has a finite size and cannot be considered a point receiver. It will measure the pressure integrated over its surface not the pressure at a point, and this must be taken into account when calculating the integral of the hydrophone signal over the whole ultrasonic beam. Phase changes may also occur over the hydrophone element. The second problem occurs with the directional response of the hydrophone as the hydrophone is scanned away from the acoustic axis of the transducer. This problem could be overcome, however, by either rotating the transducer about its front surface and performing an angular scan instead of scanning the hydrophone, or, as has been done at NPL, by rotating the hydrophone for maximum signal at each point in the scan.

Hydrophone calibration by reciprocity

The other technique at present used for hydrophone calibration at NPL is based on the two transducer reciprocity method recommended by the IEC[1]. This technique can be divided into two parts. Firstly, a transducer is calibrated using self-reciprocity by determining both the drive current and the open-circuit voltage received from a plane reflector. The acoustic pressure in the field transmitted by the transducer is then known as a function of the drive current. The hydrophone to be calibrated is then placed in the ultrasonic field and its output open-circuit voltage determined.

This technique assumes that the transducer satisfies the reciprocity condition with the factor determining the front surface movement for a certain input current when the device is used as a source being directly related to that determining the voltage generated by an applied pressure when it is used as a receiver. Another assumption used is that the ultrasonic wave is plane and corrections must be made for the non-plane nature of the wave emitted by the transducer. Further uncertainties occur in the measurement of the drive current and received voltage, particularly as this technique requires the determination of the open-circuit voltage received by both the transducer and the hydrophone at frequencies in the megahertz range.

Measurement of the output of medical equipment

As mentioned earlier, one major use of calibrated hydrophones is to determine the output from medical ultrasonic equipment, and at NPL measurements have been performed on several types of ultrasonic machines. This equipment can be divided into three broad categories depending on its use diagnostic, therapeutic or monitoring (Doppler).

(i) Diagnostic Equipment

Diagnostic equipment uses the pulse-echo technique and detects short pulses of ultrasound reflected from organs within the body. To adequately characterise the field from this type of equipment, it is necessary to measure the shape of the ultrasonic pulse. Conventional hydrophones, however, typically consist of small ceramic piezoelectric elements mounted on the end of a needle-like probe, and, in general, these devices may be unstable and have highly frequency dependent response characteristics, introducing possible sources of error in the measurement of pulsed fields. A different approach based on membrane hydrophones is used at NPL[2,3.] These hydrophones consist of a piezoelectric plastic, pvdf, in the form of a thin membrane which is stretched over an annular frame large enough to allow the entire ultrasonic beam to pass through the central aperture. A small central region of the membrane is coated with metal electrodes and polarised to introduce piezoelectric properties within that small region. This type of hydrophone is stable and possesses a broadband frequency response making it suitable for the accurate determination of pulse shape.

A further problem posed by much diagnostic equipment is the use of complex sources to enable the "real time" visualisation of structures within the human body. In one widely-used method, many small transducer elements are mounted on a single head in the form of a linear array. A small number of adjacent elements are activated simultaneously to generate a single pulse-echo image line, with the next pulse being excited from a different group of elements and producing a closely adjacent image line. The line-to-line switching is carried out sufficiently rapidly to produce a real-time image as wide as the length of the linear array. Governmental requirements in the United States [4] require the measurement of parameters such as the total ultrasonic power, the spatial average temporal average intensity and the spatial peak pulse average intensity from these complex sources. The total power could be measured in some type of radiation pressure balance, but as the transducer head is large (typically 10 cm) and the total power small (typically less than 5 mW), the construction of a balance with a target large enough to intercept the beam and sufficient mechanical isolation to accurately measure the low powers may not be practical. At NPL, the total power from linear array transducers and other complex sources is, at present, determined by scanning a hydrophone over the ultrasonic beam and integrating, which, although time-consuming, produces reliable results. Another difficulty with complex sources occurs in obtaining an accurate concept of the quantity required, and this is especially apparent in the determination of the ultrasonic beam cross-sectional area. For one particular group of elements, this area can be unambiguously defined as the area where, during the activation of this group of elements, the pressure is above a certain value. For the whole linear array, however, the area in space being irradiated varies with time as one group of elements after another is activated. There are, therefore, two possible interpretations of the term "beam cross-sectional area" for a linear array. One option is the sum of the individual areas measured for each group of elements. However, because these individual areas may overlap, there is an alternative area defined by the locus of the points in space where during the complete scanning cycle the pressure is above a certain value. Clearly, different values of parameters such as the spatial average intensity will be obtained in each case, as the area of spatial averaging will be different.

(ii) Therapeutic Equipment

Completely different problems occur in the characterisation of therapeutic equipment where the ultrasound is usually continuous and much higher ultrasonic powers are used. In this case, the FDA standard [5] requires the measurement of the temporal average ultrasonic power and the temporal average effective intensity. The temporal average power can be determined sufficiently accurately using a radiometer such as that described in [6]. Determination of the intensity parameter poses more problems as this is defined as the ratio of the ultrasonic power to the effective radiating area, where this is the area consisting of all points on a surface 5 mm from the transducer face with an intensity of 5% or more of the maximum intensity. The peak acoustic pressure in the field may be much greater then 10^6 Pa, and, at NPL, it has been found that probe hydrophones are destroyed in these fields, probably by cavitation. Membrane hydrophones, however, can be used without any apparent ill effects, but they introduce their own problem as reflection from the membrane surface produces standing waves between the transducer front surface and the membrane. However, this can be reduced by using thinner membranes. Another much more fundamental problem occurs in the meaning of the term intensity at small distances from the transducer face. Determination of intensity with a hydrophone is based on the measurement of pressure, together with the equation,

$$I = pv = p^2/\rho c.$$

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This equation assumes that the pressure p and velocity v are in phase. At 5 mm from the transducer surface, however, this is not the case and the difference between the true intensity and that determined from hydrophone pressure measurements is of the order of 35% for a 30 mm diameter transducer.

(iii) Doppler Equipment

If an ultrasonic wave is scattered by a moving object, then the scattered wave is frequency shifted, and this Doppler shift can be used to examine movements within the body. In Doppler equipment, the ultrasound is usually continuous, but as much smaller transducers and focussed fields are used, any resonances between the transducer and hydrophone are greatly reduced. The focussing and transducer size introduces its own problems, however, as the resultant field, particularly at the focal area, will be very small and small hydrophone elements will be needed to provide adequate field details.

1. IEC draft standard to TC29D-WG4. The characteristics and calibration of hydrophones for operation in the frequency range 0.5 MHz to 15 MHz.

2. K C SHOTTON, D R BACON and R M QUILLIAM 1980 Ultrasonics 18 123-126. A pvdf membrane hydrophone for operation in the range 0.5 MHz to 15 MHz.

3. D R BACON 1982 IEEE Trans. Sonics and Ultrasonics SU-29 18-25 Characteristics of a pvdf membrane hydrophone for use in the range 1-100 MHz.

4. HHS Publication (FDA) 81-8145 Diagnostic ultrasound reporting guide.

5. FRD 78-4367 Ultrasonic therapy products: radiation safety performance standard.

6. K C SHOTTON 1980 Ultrasound in Med. & Biol. 6, 131-133. A tethered float radiometer for measuring the output power from ultrasonic therapy equipment.