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UK NATIONAL MEASUREMENT STANDARDS FOR MEDICAL ULTRASONICS AND THEIR DISSEMINATION

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INTRODUCTION

The National Physical Laboratory (NPL) has the responsibility in the United Kingdom for the establishment of primary standards of measurement and for the dissemination of these standards. In ultrasonics, the emphasis has been on the development of the necessary standards and measuring techniques for the determination of the acoustic output of medical ultrasonic equipment in the megahertz frequency range. Such standards provide a common basis for meaningful comparison between measurements made by manufacturers and users. They also provide the basis for possible international standardisation of both acoustic output labelling requirements for equipment and for setting exposure limits, both of which are the subject of current debate.

Two primary standards have been developed. The first is the radiation-pressure balance for the determination of total ultrasonic power and the second is the laser optical interferometer for the determination of acoustic pressure. Both of these primary standards can be used for the calibration of reference hydrophones, which are then used to calibrate customers' hydrophones or for measuring the acoustic output of customers' transducers and equipment. These represent the main methods for the dissemination of the primary standards and are shown schematically in Figure 1 together with other relevant cross-links.

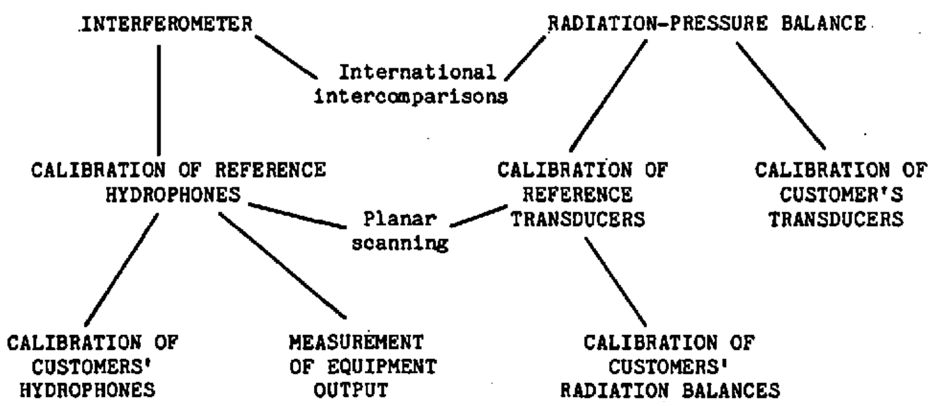

Figure 1. UK National standards for medical ultrasonics and their dissemination.

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PRIMARY STANDARDS

Radiation-pressure balance

The total time-averaged output power from an ultrasonic transducer is measured using the radiation-pressure balance shown in Figure 2, which consists of a totally-reflecting target suspended in a water-bath from one arm of a fully-compensating, servo-controlled microbalance. The transducer to be calibrated is mounted in the water-bath directly below the target and can be adjusted in a horizontal plane to be centralised with the target; the target/transducer separation can also be adjusted. The ultrasound impinges on the target, which experiences a force due to the momentum carried by the ultrasonic wave. This force changes the apparent weight of the target and the change is measured using the microbalance. The weight change, F, is related to the total power, P, of the transducer by P = Fc where c is the velocity of sound in water. After extensive theoretical and experimental studies [1,2] of the performance of the radiation-pressure balance, it has been shown that the NPL device can be used over the range 0.1 to 500 mW with an estimated uncertainty of less than ± 3% at frequencies up to 5 MHz. Above 5 MHz additional sources of uncertainty such as streaming and convection effects became important, consequently uncertainties can be as high as ± 10% at 15 MHz.

Although there are major limitations to the general applicability of this radiation-pressure balance to measurements of the total output power from medical ultrasonic equipment, the system remains the most accurate method in use at NPL for the determination of total ultrasonic power emitted by simple ultrasonic transducers. The limitations of the system are mainly associated with the size of the target (50 mm diameter) and the fact that only the momentum of the beam in the vertical direction is measured. Hence, the balance cannot readily be applied to measurements of linear-array, phased-array or sector scanners when operating in the scanning mode, or to other systems which generate wide or divergent ultrasonic beams.

An important aspect of NPL's role in establishing national standards is its involvement with other national standardising laboratories, often through participation in international intercomparisons. These serve to justify the independent assessment of the absolute accuracy of a primary standard, especially when the other laboratories use independent methods. Such an intercomparison was organised by the US National Bureau of Standards [3] in which a group of quartz transducers operating at 2 or 5 MHz were circulated to various laboratories. Although radiation-pressure balances using different principles of operation were employed by most participants, calorimetry and reciprocity were also used. The difference between the NPL measurements and the grand mean was 4-5% at 2 MHz and less than 1% at 5 MHz.

Interferometer

Although total power is an important acoustical parameter, the specification of the acoustic output of medical ultrasonic equipment is often in terms of intensity parameters derived from measurements of the spatial and temporal distribution of acoustic pressure using miniature hydrophones. Such measuring devices need to be calibrated in order to determine their sensitivity to acoustic pressure. At NPL, the primary calibration of hydrophones is carried out using the laser interferometer facility shown in Figure 3. This is based on a phase-locked Michelson interferometer developed by AERE Harwell and applied to

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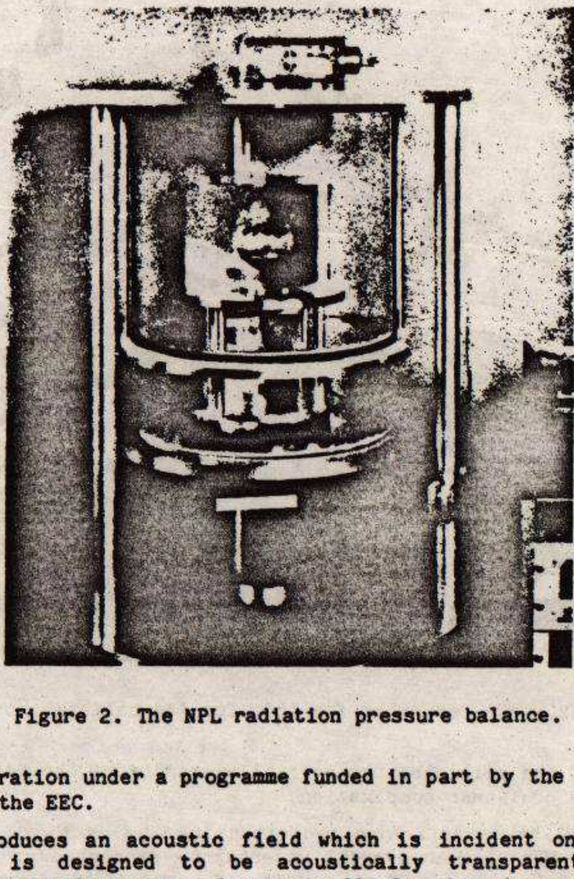

Figure 2. The NPL radiation pressure balance.

hydrophone calibration under a programme funded in part by the Community Bureau of Reference of the EEC.

A transducer produces an acoustic field which is incident on a thin plastic pellicle which is designed to be acoustically transparent but optically reflecting. The displacement of the pellicle is determined using the interferometer and the corresponding acoustic pressure is derived from this measurement. A hydrophone is then placed at the same place in the field and calibrated by measuring the output voltage corresponding to the known acoustic pressure. The laser interferometer constitutes an ideal primary standard because the measurements are directly traceable to primary standards of length and it is insensitive to the characteristics of the acoustic field.

Much of the development work on the interferometer involved improving the signal-to-noise ratio in order to detect and measure the very small ultrasonic displacements involved (0.3 to 7 nm). An effective noise level of 0.013 nm has been achieved mainly through improved rejection of environmental vibration, low-noise electronics, and narrow-band filters. An extensive study of sources of systematic uncertainty has been undertaken, including those arising from the interaction of the optical beam with the acoustic field, the acoustical

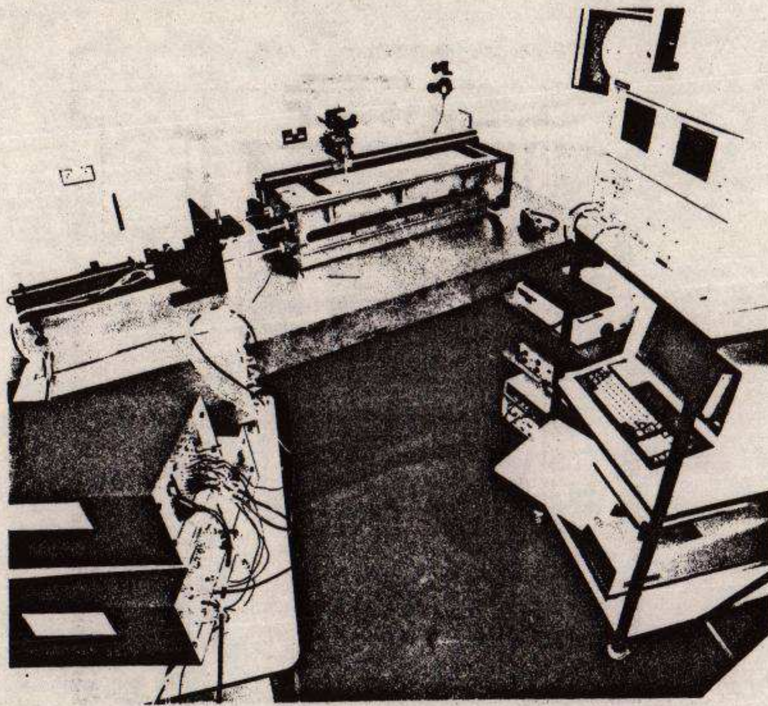

Figure 3. The NPL interferometer facility for the calibration of hydrophones.

transmission of the pellicle, the spatial averaging of the acoustic field by the hydrophone, and nonlinear propagation.

Using this facility, a reference hydrophone can be calibrated in the frequency range 0.5 to 15 MHz with an overall uncertainty expressed at the 95% confidence level of ± 2% at 0.5 MHz, ± 3% at 5 MHz, ± 3.5% at 10 MHz, and ± 6.5% at 15 MHz. Calibrations based on the optical interferometer have been shown (Figure 4) to be in agreement with those obtained using alternative techniques such as reciprocity and planar scanning [4], although the uncertainties of these other methods are two or three times larger. Comparison between the interferometry and planar-scanning techniques provides the cross-link, illustrated in Figure 1, between the two primary standards.

Whilst informal intercomparisons of hydrophone calibration techniques have been undertaken between NPL and other laboratories in which agreement has been within the combined uncertainties, no formal intercomparison has yet been undertaken. It is, however, planned that such an intercomparison will take place within the EEC in the future.

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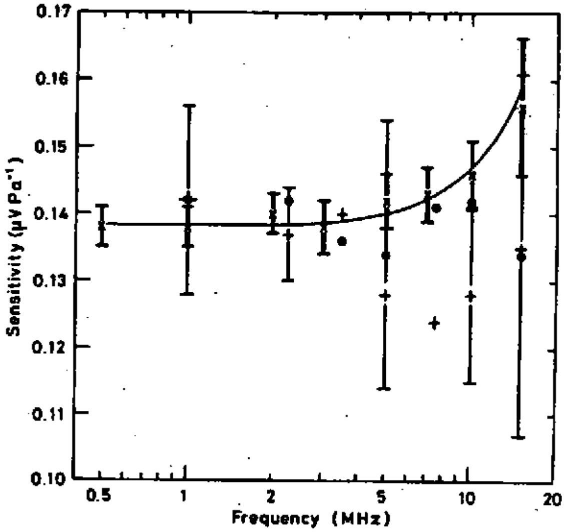

Figure 4. Sensitivity of a pvdf membrane hydrophone as a function of frequency based on three methods [4]; the continuous curve represents the theoretical model of Bacon [6] (NB The error bars are based on a linear summation of sources of systematic uncertainty).
- \+ Planar scanning
- ● Reciprocity
- x Interferometry

DISSEMINATION OF STANDARDS

There are a number of methods by which the national primary standards are disseminated. The calibration of hydrophones represents the most important method although others, such as the measurement at NPL of the acoustic output of ultrasonic equipment, the calibration of customers' radiation-pressure balances and the use of equipment made to NPL design, are also mechanisms for providing traceability to national standards.

Hydrophone calibration

The calibration of customers' hydrophones at NPL involves a substitution procedure; laser interferometry is used to calibrate a stable reference hydrophone and then a relative method is used to transfer this calibration to the customer's device. This method is used because the interferometry is so time consuming. The reference hydrophones are of the membrane type which have been developed jointly between NPL and the Marconi Research Centre [5-7]; they exhibit a smooth frequency response and the particular frequency chosen for calibration is not critical.

Although a single-frequency procedure is satisfactory for membrane hydrophones and has been the main method used at NPL, the calibration of hydrophones which exhibit structure in their frequency response require a continuous or multiple-frequency method. To meet this requirement, a method has been developed at NPL using an acoustic field containing many harmonically-related frequency components. The method used to generate such a field utilises the distortion of an acoustic pulse waveform due to nonlinear propagation. Intercomparisons with the discrete-frequency technique have shown agreement within the combined random uncertainties and this method will be implemented on a routine basis in the future.

The overall uncertainty at 95% confidence in the calibration of the end-of-cable open circuit sensitivity of a customer's hydrophone is ± 4.5% at 1 MHz, ± 5.5% at 5 MHz, ± 6.5% at 10 MHz, and ± 9.2% at 15 MHz.

Acoustic output measurements

Calibrated hydrophones are used at NPL for the measurement of the acoustic output of medical ultrasonic equipment as part of the Ultrasound Measurement Service offered to customers, and this represents another method of disseminating the primary standards. An extensive beam-plotting facility is used which has microcomputer-controlled coordinate-positioning systems for both the transducer and the hydrophone and a waveform digitising system. A range of membrane hydrophones is available, the choice depending on the requirements of the ultrasonic field, and devices made from polyvinylidene fluoride (pvdf) of thickness 0.009 mm or 0.025 mm with active elements of diameter 0.5, 1, 2 or 4 mm are used. Although coplanar shielded types are used for most work, bilaminar and differential-output types are available if required [7].

From measurements of the spatial and temporal distribution of acoustic pressure, various acoustical parameters are determined and Table 1 provides guidance to the accuracy which can be achieved. These are typical values for measurements made on a sector scanner operating in scanning mode using a 0.5 mm active element hydrophone, and overall uncertainties are expressed at 95% confidence level.

Table 1 Typical uncertainties for acoustic output measurements of a 3.5 MHz sector scanner operating in scanning mode

Peak-positive acoustic pressure	± 20%
Peak-negative acoustic pressure	± 8%
Spatial-peak pulse-average derived intensity	± 14%
Spatial-peak temporal-average derived intensity	± 15%
Beam-average temporal-average derived intensity	± 15%

Other dissemination methods

A number of other methods are used for the dissemination of the primary standards, one such being the calibration of radiation-pressure balances by direct intercomparison with the primary standard; stable reference transducers are used as the transfer standards for this procedure. Another type of dissemination takes place when measuring equipment which has been developed and validated at NPL is used elsewhere, an example of this being the tethered-float radiometer [8]. A number of these devices have been built to the NPL design and it has been shown that these have identical performance properties within the measurement uncertainties (typically ± 5%).

A final example of dissemination, and potentially one of the most important, is the calibration of specially-developed beam calibration systems which enable rapid measurements of the acoustic output of medical ultrasonic equipment to be made. The NPL Ultrasound Beam Calibrator (BECA) is based on a multi-element pvdf hydrophone and a dedicated microprocessor data acquisition system, and provides a versatile measurement facility with a wide range of applications. Originally developed to meet the needs of the NPL Measurement Service, it is now commercially available and offers for the first time the capability to make reliable measurements in a relatively short time with the results being traceable to national standards.

CONCLUSION

Two primary standards, namely the radiation-pressure balance and the laser interferometer, are briefly described. These have been developed as the basis of the UK national measurement standards for the determination of the acoustic output of medical ultrasonic equipment. Typical accuracies achieved and the various methods of dissemination are discussed with particular emphasis on the calibration of hydrophones.

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