Beam profile measurement on HITU transducers using a thermal intensity sensor technique

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Abstract. Thermal intensity sensors based on the transformation of the incident ultrasonic energy into heat inside a small cylindrical absorber have been developed at PTB in the past, in particular to determine the acoustic output of medical diagnostic ultrasound equipment. Currently, this sensor technique is being expanded to match the measurement challenges of high intensity therapeutic ultrasound (HITU) fields. At the high acoustic power levels as utilized in the clinical application of HITU transducers, beam characterization using hydrophones is critical due to the possible damage of the sensitive and expensive measurement devices. Therefore, the low-cost and robust thermal sensors developed offer a promising alternative for the determination of high intensity output beam profiles. A sensor prototype with a spatial resolution of 0.5 mm was applied to the beam characterization of an HITU transducer operated at several driving amplitude levels. Axial beam plots and lateral profiles at focus were acquired. The absolute continuous wave output power was, in addition, determined using a radiation force balance.

1. Introduction
The determination of the acoustic output of medical ultrasound equipment is important as regards aspects of quality assurance and the safety of the patient. The procedures to measure and characterize the ultrasound beams are described in several international standards for diagnostic and physiotherapy devices. These standards are continuously developed to comply with the technical progress and increasing fields of application of ultrasound equipment. More recent developments of using high intensity therapeutic ultrasound (HITU) for the ablation of tumors require new methods and standards for characterizing the high power transducers [1]. The measurements are usually performed using radiation force balances to determine the output power and using hydrophones to determine local pressure and intensity parameters. However, hydrophone measurements are difficult in the case of HITU fields at high clinical power levels since these sensors may easily be damaged when scanning the focus region. Damage and measurement distortion may occur due to heating, cavitation, and radiation force. As an alternative to the hydrophone-based technique, the local temporal-average ultrasound intensity and beam dimensions can be measured using thermal sensors. This technique – based on the transformation of the incident ultrasonic energy into heat inside a small cylindrical absorber – was developed at PTB in the past, in particular to determine the acoustic output of medical diagnostic ultrasound equipment [2,3,4]. Currently, this sensor technique is being expanded to match the measurement challenges of HITU fields. This paper describes the application of a novel sensor prototype with a spatial resolution of 0.5 mm to the beam characterization of an HITU transducer.
operated at several driving amplitude levels. Axial beam plots and lateral profiles at focus were acquired. The absolute temporal-average output power was, in addition, determined using a radiation force balance.

2. Sensor principle and design considerations

The thermal measurement technique used is based on the transformation of the incident ultrasonic energy into heat within a small-sized cylindrical absorber (figure 1). The front face of the absorber is in contact with the surrounding water to allow the ultrasound wave to pass into the absorber. Due to this contact, the temperature at the absorber front face is the same as in the water bath. Since the absorber is in part thermally insulated by an air-filled housing, the temperature at the rear increases during insonation. Part of the heat produced inside the absorber permanently flows through the front face to the water. After a period of insonation with constant intensity, thermal equilibrium will appear between the heat produced by absorption and the heat given off to the surrounding water. From the temperature enhancement $\Delta T$ at the rear of the absorber at this equilibrium measured by a small resistor temperature probe, the ultrasound intensity averaged over the absorber cross section can be determined [5]. Since all thermal processes are slow in comparison with the ultrasound frequencies and the repetition frequencies of bursts, the sensor inherently temporally averages over all incident waveforms. In contrast to the plexiglas absorbers formerly used for diagnostic ultrasound [3], the absorber material applied here is polymethylpentene, providing an acoustic impedance of $\rho c = 1.69 \times 10^6$ kg m$^{-2}$ s$^{-1}$, being better matched to that of water. It is expected that this will reduce the frequency response variations due to lower multi-reflections within the absorber rod. However, this has to be confirmed by future calibration measurements. The absorber sizes are 0.5 mm in diameter and 2 mm in length. A steel housing is used to enhance the robustness of the sensor and to increase the cooling of the absorber at the front face rim. Finally, a conical shape for the front of the housing was chosen to reduce acoustic reflections between the sensor and the source transducer which led to distortions of measurements at short distances with the previous planar sensors [4].

![Figure 1. Left: thermal ultrasound intensity sensor. The intensity of the ultrasonic wave is determined from the temperature increase $\Delta T$ at equilibrium measured at the rear of an absorber. Right: photograph of the prototype sensor.](image)

3. Comparison measurement of a diagnostic ultrasound field

To test the new sensor prototype manufactured, comparison measurements of a high intensity pulse Doppler field of a commercial diagnostic machine were performed first. The set-up for the intensity scans is depicted in figure 2. The 3.5 MHz convex array transducer is slightly immersed into the degassed and deionized water contained in a measurement tank and adjusted to emit the ultrasound
beam vertically downwards. The thermal sensor is mounted onto a stepper motor-driven xyz-positioning system which is controlled by a computer. The measurement software program controls the sensor movement for axial scans (z-direction) and for beam profile line scans in the azimuth and elevation directions (x- and y-directions, respectively) and records the data from the temperature probe of the ultrasound sensor and from a second probe for the water bath reference temperature. The sound field axis was determined by lateral maximum search at two distances from the transducer: The nominal focal length of the elevational lens and 30 mm beyond that distance. Then a line scan was performed along this axis to obtain the axial beam profile. Afterwards, at the distance of maximum intensity, lateral beam profiles were measured in azimuthal and elevation directions. The temperature-versus-time curves recorded were automatically evaluated regarding the equilibrium temperature enhancement in comparison to the switched-off condition of the transducer. The measurement time for one line-scanning step including the time to reach equilibrium and the time to average 20 data points at equilibrium was about 60 s. A mechanical stirrer was used to achieve a homogeneous temperature distribution in the water bath and to avoid clouds of warmth in front of the thermal sensor front face. An additional acoustic absorber avoided backreflections from the bottom of the tank. The temperature data of the new HITU intensity sensor were compared with the results of the previously calibrated 0.6 mm diameter sensor as given in [4]. By equally scaling the data at the position of maximum intensity as shown in figure 3, the temperature-to-intensity transfer factor of the HITU sensor was estimated to be approximately $H(3.5 \text{ MHz}) = 0.17 \text{ mK W}^{-1} \text{ m}^2$. In addition, the result of a needle hydrophone measurement is shown in figure 3. The comparison of the curves shows good agreement. The systematic overestimation of the planar thermal sensor at distances below 28 mm due to multi-reflections between the sensor and the transducer is significantly reduced with the conical HITU intensity sensor design.

![Figure 2. Set-up for intensity scans using the thermal sensor technique.](image-url)
4. Measurement of HITU fields

The performance of the HITU intensity sensor was tested in the field of a 64 mm diameter HITU source transducer (Sonic Concepts Inc., model H-101) driven by a signal generator (Tektronix, AFG 3251) and power amplifier (Electronics&Innovation Ltd., model 350L) at a working frequency of $f = 1.06$ MHz. The measurement set-up was similar to that depicted in figure 2, with the difference that the transducer was mounted at a side wall of the water tank with the sound beam axis being horizontally aligned. The measurements of the beam profiles in axial and lateral directions were performed in burst mode using 20 cycles and a pulse repetition period of $prp = 1$ ms for three different driving levels. The results are depicted in figure 4. The profile data are given in the form of temperature increases here, since the temperature-to-intensity transfer factor at 1 MHz has not been determined so far by an absolute calibration. The full width at half maximum beam dimensions obtained are $d_x = 1.5$ mm, $d_y = 1.4$ mm, and $d_z = 9.2$ mm. The beam width at focus and the position of the focus do not depend on the driving levels used. In addition to the beam plots, the continuous wave temporal-average output power $P_{cw}$ of the transducer was determined by a radiation force balance measurement. The continuous wave power levels used were 5 W, 15 W, and 25 W. For higher driving levels, cavitation led to distortions in the thermal sensor measurements. Improvements may be possible using permanent degassing of the water and by using chemical additives. Furthermore, a smoother front face at the absorber-housing transition may shift the occurrence of cavitation towards higher driving levels.

Figure 3. Beam plots in the axial direction obtained by two different thermal sensors and by needle hydrophone measurements for the high intensity pulse Doppler mode of a diagnostic 3.5 MHz convex array transducer.
5. Conclusions
A thermal sensor technique for local intensity measurements has previously been applied successfully to the acoustic output characterization of diagnostic ultrasound devices and provides an easy way of overall intensity determination. The simple principle of operation and the robustness of the sensors are principal advantages, for instance, in comparison to hydrophones, which are much more sophisticated, and the concept has been further developed here to address the specific measurement challenges in the case of high intensity therapeutic ultrasound. A new prototype with a different absorber material, reduced sensitivity, increased robustness, and less distortions formerly caused by reflections between the sensor and the transducer has been manufactured and tested. The first HITU output beam characterization measurements were performed. Currently, the measurements are limited regarding the driving level by the occurrence of cavitation leading to distortions of the beamprofiles acquired due to acoustic and thermal shielding of the sensor front face. Another limitation is given by the burst length. For duty factors above 0.3, distortions were observed. To verify the option of intensity profile measurement at reduced burst lengths compared to the clinical settings, future investigations are planned to investigate the linearity of the output power of typical HITU transducers with burst lengths up to continuous wave operation using the radiation force balance.
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References
[1] IEC 2010 Requirements for measurement standards for high intensity therapeutic ultrasound (HITU) devices (Geneva: International Electrotechnical Commission Publication Technical Report 62649 Ed.1)
[2] Wilkens V and Reimann H-P 2004 Output intensity measurements on a diagnostic ultrasound machine using a calibrated thermoacoustic sensor Journal of Physics: Conference Series 1 (Advanced Metrology for Ultrasound in Medicine UK IOP Publishing) p 140-5
[3] Wilkens V 2010 A thermal technique for local ultrasound intensity measurement, part 1: Sensor concept and prototype calibration Meas. Science Technol. submitted for publication
[4] Wilkens V 2010 A thermal technique for local ultrasound intensity measurement, part 2: Application to exposimetry on a medical diagnostic device Meas. Science Technol. submitted for publication
[5] Fay B and Rinker M 1996 Determination of absolute value of ultrasonic power by means of thermoacoustic sensors Acustica 82 274-9