Output intensity measurement on a diagnostic ultrasound machine using a calibrated thermoacoustic sensor

To cite this article: Volker Wilkens and Hans-Peter Reimann 2004 J. Phys.: Conf. Ser. 1 140

View the article online for updates and enhancements.

Related content

- Thermal ultrasound intensity sensors: concept and prototype calibration
  V Wilkens

- Thermal ultrasound intensity sensors: application to exposimetry
  V Wilkens

- Beam profile measurement on HITU transducers using a thermal intensity sensor technique
  V Wilkens, S Sonntag and K-V Jenderka

Recent citations

- Design of a Thermoacoustic Sensor for Low Intensity Ultrasound Measurements Based on an Artificial Neural Network
  Jida Xing and Jie Chen

- Design and Characterization of a Close-Proximity Thermoacoustic Sensor
  Jida Xing et al

- Beam profile measurement on HITU transducers using a thermal intensity sensor technique
  V Wilkens et al
Output intensity measurement on a diagnostic ultrasound machine using a calibrated thermoacoustic sensor

Volker Wilkens and Hans-Peter Reimann

Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

E-mail: Ultrasonics@ptb.de

Abstract. A thermoacoustic measurement technique based on the transformation of the incident ultrasonic energy into heat inside a cylindrical absorber is investigated. To enable quantitative acoustic intensity measurements, a thermoacoustic sensor with an absorber 3 mm in diameter is calibrated in the far field of a planar source transducer. For ultrasound frequencies in the range from 1 to 9 MHz, the time-averaged intensities are derived from pressure field measurements using a membrane hydrophone. In a second run, measurements are performed with the thermoacoustic sensor at the same position in the acoustic field and under the same excitation conditions. The equilibrium temperature enhancement at the rear side of the absorber is determined at each frequency, and the transfer function of the sensor is given by the temperature enhancement per ultrasound intensity averaged over the sensor cross section. The calibrated thermoacoustic sensor is then applied to acoustic output measurements on a diagnostic ultrasound machine at various parameter settings. The results for M-mode and pulse Doppler mode, i. e. for non-scanning beams, are compared with the intensities derived from additional hydrophone measurements. If the spatial averaging effect of the thermoacoustic sensor is taken into consideration, agreement can be observed between the results of both methods.

1. Introduction
Ultrasound exposure measurements on medical ultrasound systems are essential as regards aspects of safety and quality assurance. Commonly, the acoustic output of ultrasound machines is determined by hydrophone measurements using raster scanning or by power measurements with radiation force balances. The determination of time-averaged ultrasonic intensities using hydrophone measurements can be quite cumbersome in particular for scanning modes and combined modes of the ultrasound machine [1]. To include all contributing ultrasonic waves at the measurement position, a sophisticated synchronization setup is necessary and also much insight into the operation modes of the device under test, as is usually only available to the manufacturer. Thermoacoustic sensors are a very simple and low cost alternative to hydrophone measurement based intensity determination methods providing time-averaged intensities without the need for synchronization to individual ultrasonic pulses and pulse sequences.

The thermoacoustic measurement technique investigated is based on the transformation of the incident ultrasonic energy into heat inside a cylindrical absorber and the detection of the temperature rise on the rear side of the absorber. To enable quantitative acoustic intensity measurements, a
thermoacoustic sensor is calibrated in the far field of a planar source transducer. For ultrasound frequencies in the range from 1 to 9 MHz, the acoustic pressure fields are measured using a calibrated membrane hydrophone and the time-averaged intensities are calculated using plane wave assumptions. In a second run, measurements are performed with the thermoacoustic sensor at the same position in the acoustic field and under the same excitation conditions. The equilibrium temperature enhancement at the rear side of the absorber is determined, and the frequency dependent transfer function of the sensor is given by the temperature enhancement per ultrasound intensity averaged over the sensor cross section. The calibrated thermoacoustic sensor is then applied to acoustic output measurements on a diagnostic ultrasound machine at various parameter settings. The results for M-mode and pulse Doppler mode, i.e., for non-scanning beams, are compared with the intensities derived from independent hydrophone measurements.

2. Principle of operation

The thermoacoustic measurement technique used is based on the transformation of the incident ultrasonic energy into heat inside a cylindrical plexiglas absorber (figure 1) [2]. The absorber is in part thermally insulated by an air-filled housing, and only the front face is in contact with the surrounding water to allow the ultrasound wave to get into the absorber. Due to this contact, the temperature of the front face is equal to that of the surrounding water, while at the rear side the temperature increases. Part of the heat produced inside the absorber permanently flows through the front face of the absorber to the water. Assuming the acoustic intensity \( I \) of the ultrasonic wave is constant for a sufficiently long time, thermal equilibrium will appear between the heat produced by ultrasound absorption and the heat given off to the surrounding water. From the temperature enhancement at the rear side of the absorber at equilibrium measured by a small resistor temperature probe, the ultrasonic intensity averaged over the sensor cross section can be determined.

![Figure 1. Thermoacoustic sensor setup. The intensity \( I \) of the ultrasonic wave is determined from the temperature increase measured at the rear side of an absorber.](image1.png)

3. Sensor calibration

3.1. Thermal calibration

After manufacturing of a thermoacoustic sensor with a plexiglas absorber 3 mm in diameter and 4 mm in length, a thermal calibration measurement was performed to determine the relation between the electrical resistance of the individual temperature probe and the absorber temperature.

![Figure 2. Thermal calibration curve of a thermoacoustic sensor. The parameters obtained by fitting of the experimental data are used for resistance to temperature conversion in the acoustic measurements.](image2.png)
The absorber was slowly heated in a stirred water bath and the resistance as well as the water bath temperature, measured with a calibrated thermometer, were recorded. The temperature probe used provided a logarithmic dependence of the temperature on the resistance as depicted in figure 2. The thermal calibration result obtained is used for resistance to temperature conversion within the measurements described in the following.

3.2. Acoustic calibration
To enable quantitative acoustic intensity measurements, the thermoacoustic sensor was acoustically calibrated. The measurement setup is depicted in figure 3. Two plane single element source transducers (Panametrics, diameter: 19.05 mm and 6.35 mm, center frequencies: 2.25 MHz and 5 MHz, respectively) were used to generate ultrasonic tone bursts in the frequency range from 1 to 4 MHz and from 4 to 9 MHz successively with frequency steps of 0.1 MHz. The transducer was driven by a synthesizer (Wavetek model 81) and an amplifier (RF Power Labs model 150C). Control of the output voltage of the amplifier was performed by an oscilloscope (Tektronix TDS 744 A). In a first measurement run (A), the acoustic pressure in the far field of the transducer (distance $z = 250$ mm) was measured in a water tank by means of a coplanar membrane hydrophone (Marconi, 0.5 mm nominal diameter). The tank walls behind the hydrophone and the source transducer were covered with acoustic absorbers. To avoid disturbance of the hydrophone measurement of the direct ultrasonic wave by reflections, the pulse duration was limited at the synthesizer to 20 cycles with a repetition rate of $1/(900 \mu s)$. The output voltage of the hydrophone was amplified (in-house customized broadband amplifier), and the voltage amplitude was measured in the middle part of the tone burst by means of the oscilloscope and stored in a computer which additionally controlled the hydrophone positioning stepper motors. Signal averaging was performed to enhance the signal to noise ratio. A $5 \times 5$ mm raster scan centered at the position of the maximum amplitude was performed with steps of 0.5 mm.

![Figure 3](image_url)

**Figure 3.** Experimental setup for the acoustic calibration of the thermoacoustic sensor; A: hydrophone raster scan, B: thermoacoustic sensor measurement.

From the measured voltage $U(x,y,f)$ the acoustic pressure amplitude was calculated at each position:

$$p(x, y, f) = \frac{U(x, y, f)}{M(f)},$$

where $M(f)$ denotes the voltage to pressure transfer function of the in-house calibrated hydrophone amplifier combination. From the measured pressure amplitudes, the time-averaged acoustic intensities $I(x,y,f)$ were calculated using plane wave assumptions and extrapolation from the finite burst waves to
continuous waves, i.e. it is assumed that the transducer would generate the same pressure amplitudes for continuous harmonic excitation:

\[ I(x, y, f) = \frac{p(x, y, f)^2}{2\rho c}, \tag{2} \]

with \( \rho \) the density and \( c \) the sound velocity in water. Averaging the data \( I(x,y,f) \) which refer to a circular area with 3 mm diameter centered at the maximum intensity value, provided the spatially averaged intensities \( I_s(f) \) to be measured with the thermoacoustic sensor with 3 mm absorber diameter.

In a second run (figure 3, B), the measurements were repeated for each frequency with the thermoacoustic sensor to be calibrated which was positioned at the same distance \( z \) from the source transducer as the hydrophone was before. The change in electrical resistance of the temperature probe of the sensor was measured by an ohmmeter (Solatron 7150) and conversion to temperature values was performed by the data acquiring computer program using the experimentally determined thermal calibration data (cf. section 3.1). Lateral alignment was achieved by searching for the maximum temperature enhancement at equilibrium. A second reference temperature probe calibrated in the same way as the thermoacoustic sensor was used to simultaneously measure the water bath temperature during the acoustic measurements, and temperature drifts were compensated by evaluation of the temperature difference between the temperature probe within the thermoacoustic sensor and the reference probe. The water in the tank was stirred to avoid the generation of a heated water volume localized in front of the thermoacoustic sensor. The same electrical excitation conditions as in the hydrophone measurements were used for the source transducer with the exception of the cycle number. For each frequency, a cycle number resulting in a temporal on-to-off ratio of 1:2 was chosen. This ensured both, a reasonable signal to noise ratio for the thermoacoustic measurements at all frequencies and prevention of the source transducer from distortion due to the acoustic wave reflected at the front face of the thermoacoustic sensor. Since the thermal response time of the sensor is very large compared with the acoustic on and off periods, it can be assumed that a continuous acoustic wave of the same amplitude and frequency would lead to a 3 times larger temperature enhancement according to a 3 times larger time-averaged intensity than in the measurements of the tone bursts.

For each frequency \( f \) the temperature versus time curve was recorded for a time period of 6 minutes with the source transducer switched on, the temperature enhancement \( \Delta T \) at equilibrium was determined, and another 12 minutes followed for the cooling down of the sensor before proceeding with the next frequency setting. In principle, the measurement time can be reduced by evaluation of transient temperature profiles [3],[4], but this was not performed within the present study. The temperature to intensity transfer function \( H(f) \) as depicted in figure 4 was then calculated by:

\[ H(f) = \frac{3\Delta T(f)}{I_s(f)}. \tag{3} \]

In general, the frequency response shows an increase from \(-4 \text{ mK} \cdot \text{W}^{-1} \cdot \text{m}^2 \) at 1 MHz to \(-5 \text{ mK} \cdot \text{W}^{-1} \cdot \text{m}^2 \) at 3.5 MHz and a somewhat lower increase up to \(-5.3 \text{ mK} \cdot \text{W}^{-1} \cdot \text{m}^2 \) at 9 MHz. The decrease at low frequencies is expected to be caused by the decreasing absorption coefficient of the plexiglas absorber [3],[5]. In addition, some stronger variations of the frequency response with periods below 0.5 MHz can be observed, in particular around 2 MHz. These variations are expected to be caused by acoustic resonances within the absorber rod since the absorber length is not long enough for complete absorption of the ultrasound waves during one round trip within the absorber. Despite these variations, reasonable results can be expected for the measurement of broadband pulses as emitted from medical diagnostic ultrasound machines. Here, the pulse spectra will cover several of the absorber resonances, and an average transfer factor at the working frequency of the device under test.
as suggested by the linear regression lines in figure 4 may be used for adequate temperature to intensity conversion.

![Figure 4. Thermoacoustic sensor calibration result; experimental data and linear regression covering two frequency ranges.](image)

4. Application to output intensity measurements

The calibrated thermoacoustic sensor was applied to output intensity measurements on a commercial diagnostic ultrasound machine. Measurements were performed for M-mode and pulse Doppler (pD) mode, i.e. two nonscanning operation modes, at different distances \( z \) from the linear array transducer and with different focal distance settings \( z_{\text{focus}} \) to cover various intensity ranges and beam profile structures. Distance adjustment was controlled using the distance measurement option of the diagnostic machine during B-mode operation. During the intensity measurements simultaneous B-mode imaging was deactivated. Lateral adjustment was performed by searching for maximum temperature enhancement. A transfer factor of \( H = 5.2 \, \text{mK W}^{-1} \, \text{m}^2 \) (cf. figure 4) for the acoustic working frequency \( f = 5.2 \, \text{MHz} \) was used to calculate the intensities given in table 1 from the equilibrium temperature enhancements \( \Delta T \).

For comparison, hydrophone-based output intensity measurements were performed using the same parameter settings as for the thermoacoustic measurements. For each parameter setting given in table 1, a \( 5.2 \times 5.2 \, \text{mm} \) raster scan centered at the lateral position of maximum intensity with steps of 0.2 mm was performed with a needle-type hydrophone (Force Institutes, nominal diameter: 0.5 mm). The intensities were calculated from the pressure wave forms measured by:

\[
I = \text{PRF} \cdot \int \frac{p(t)^2}{\rho c} \, dt,
\]

where \( \text{PRF} \) denotes the pulse repetition frequency of the diagnostic machine. Table 1 shows the results \( I_0 \) for the center position and the values \( I_3 \) obtained by averaging the data which refer to a circular area with 3 mm diameter centered at the position of the maximum intensity value. As indicated by this data, the simple and low cost thermoacoustic measurement technique gives reasonable estimates of the time-averaged ultrasonic intensities if the spatial averaging effect caused by the finite diameter of the thermoacoustic sensor is taken into consideration. Typical intensity ranges of diagnostic ultrasound machines can be detected with sufficient signal to noise ratio. Regarding the deviations between the thermoacoustic and the hydrophone results given in table 1 ranging from -14\% to +18\% it should be noted that typical hydrophone calibration uncertainties in this frequency range lead to an uncertainty for ultrasonic pressure measurements of about 10\% (95\% confidence level) which already results in an uncertainty contribution for derived intensity values of the order of 20\%.
Table 1. Output intensities of a diagnostic ultrasound machine for different parameter settings as measured with a thermoacoustic sensor and as derived from hydrophone pressure measurements; numbers in percent: deviations of the thermoacoustic from the hydrophone measurement results.

<table>
<thead>
<tr>
<th>Parameter settings</th>
<th>Hydrophone measurement</th>
<th>Thermoacoustic measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$I_0$ (W m$^{-2}$)</td>
<td>$I_1$ (W m$^{-2}$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$I_3$ (W m$^{-2}$)</td>
</tr>
<tr>
<td>Mode</td>
<td>$z$ (mm)</td>
<td>$z_{\text{focus}}$ (mm)</td>
</tr>
<tr>
<td>M</td>
<td>110</td>
<td>32</td>
</tr>
<tr>
<td>M</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>M</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>pD</td>
<td>110</td>
<td>32</td>
</tr>
<tr>
<td>pD</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

5. Conclusions
A thermoacoustic measurement technique based on the transformation of the incident ultrasonic energy into heat inside a cylindrical absorber was investigated. A sensor comprising a plexiglas absorber 3 mm in diameter and 4 mm in length was calibrated in the far field of a planar source transducer in the frequency range from 1 to 9 MHz to enable quantitative acoustic intensity measurements. The calibrated thermoacoustic sensor was then applied to acoustic output measurements on a diagnostic ultrasound machine at various parameter settings. If the spatial averaging effect caused by the finite diameter of the thermoacoustic sensor was taken into consideration, agreement could be observed between the results of the thermoacoustic measurements and hydrophone-based intensity measurements performed for comparison. The investigations reveal that the simple and low cost thermoacoustic measurement technique is a useful complement to the measurement tools applied to exposimetry on medical ultrasound equipment.

Future investigations are planned to reduce the resonance effects in the frequency response of the thermoacoustic sensor, for instance by use of absorber materials with less acoustic impedance mismatch to water. Also sensors with reduced cross section of the absorber would be desirable to allow intensity measurements with enlarged spatial resolution. Furthermore, validation for exposure measurements at scanning and combined modes of diagnostic ultrasound machines by comparison with hydrophone-based intensity determination should be provided to be able to fully exploit the advantages of the thermoacoustic measurement technique for time-averaged intensity determination.

6. References