DESIGN AND CHARACTERIZATION OF A CLOSE-PROXIMITY THERMOACOUSTIC SENSOR

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Abstract—Although the radiation force balance is the gold standard for measuring ultrasound intensity, it cannot be used for real-time monitoring in certain settings, for example, bioreactors or in the clinic to measure ultrasound intensities during treatment. Foreseeing these needs, we propose a close-proximity thermoacoustic sensor. In this article, we describe the design, characterization, testing and implementation of such a sensor. We designed a 20-mm-diameter plexiglass sensor with a 2-mm-long absorber and tested it against low-intensity pulsed ultrasound generated at a 1.5-MHz frequency, 20% duty cycle, 1-kHz pulse repetition frequency and intensities between 30 and 120 mW/cm². The sensor captures the beam, converts the ultrasound power into heat and indirectly measures the spatial-average time-average ultrasound intensity \(I_{\text{sata}}\) by dividing the calculated power by the beam cross section (or the nominal area of the transducers). A thin copper sheet was attached to the back face of the sensor with thermal paste to increase heat diffusivity 1000-fold, resulting in uniform temperature distribution across the back face. An embedded system design was implemented using an Atmel microcontroller programmed with a least-squares algorithm to fit measured temperature-versus-time data to a model describing the temperature rise averaged across the back side of the sensor in relation to the applied ultrasound intensity. After it was calibrated to the transducer being measured, the thermoacoustic sensor was able to measure ultrasound intensity with an average error of 5.46% compared with readings taken using a radiation force balance.

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Key Words: Low-intensity pulsed ultrasound, Thermoacoustic sensor, Ultrasound intensity measurement.

INTRODUCTION

Ultrasound has a wide range of biomedical applications, from imaging to promoting cell growth (Shaw and Hodnett 2008). For biological experiments, it is important to regulate the acoustic output to ensure the quality and consistency of each trial. If not monitored properly, the under-application of ultrasound in high-intensity focused ultrasound (HIFU)-based kidney stone disintegration can lead to incomplete treatment, whereas the over-application of ultrasound in low-intensity pulsed ultrasound (LIPUS) applications can lead to cell death (Shaw and Hodnett 2008). Acoustic output parameters are typically evaluated using a hydrophone or a radiation force balance. Hydrophones are considered the universal instrument for characterization of acoustic field parameters, such as pressure waveforms and beam profiles. For determining ultrasound output power, the accepted technique is the use of a radiation force balance (Shaw and Hodnett 2008). However, both of these techniques have their limitations. Operation of a hydrophone can be technically difficult, time consuming and expensive (Wilkens 2004, 2010a). On the other hand, a radiation force balance is constrained by the setup apparatus required; the ultrasound beam must be transmitted into a chamber containing degassed water onto an absorbing or reflecting target, which must intercept the entire beam (Shaw and Hodnett 2008). Because of these drawbacks, the development of another sensor design is desirable.

Thermoacoustic sensors that measure the transformation of the incident ultrasonic energy into heat have the potential to be an alternative approach to determination of ultrasound intensity. These sensors are based on the transformation of incident ultrasonic energy into heat inside a small cylindrical absorber and the detection of the temperature rise on the rear side of the absorber (Wilkens 2010a). Previous thermoacoustic sensor operation has required the

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sensor and transducer to be placed in a large water tank, similar to what is done in hydrophone or radiation force balance measurements (Fay and Rinker 1996a; Fay and Rinker 1996b; Fay et al. 1994; Wilkens 2002, 2004, 2010a, 2010b). To further simplify thermoacoustic sensor operation, we designed and tested a close-proximity thermoacoustic sensor that can determine radiated ultrasound intensities by directly coupling a transducer via a coupling medium. Compared with the previous thermoacoustic sensors that cannot take measurements without placement of the sensor and transducer in a large water tank, the close-proximity thermoacoustic sensor can take measurements in air without complicated setup procedures.

Previously developed thermoacoustic sensors have mostly used the relationship between the equilibrium temperature reached by the thermoacoustic sensor and the incident ultrasound intensity to indirectly measure ultrasound intensity (Fay et al. 1994; Wilkens 2004, 2005, 2010a, 2010b). However, this model requires an impractical amount of time for quick measurement. For instance, it takes 400 s to reach equilibrium (or 28°C, corresponding to an ultrasound intensity of 40 mW/cm²). To quickly measure ultrasound intensity, we have implemented an algorithm that determines the incident ultrasound intensity by fitting the temperature-versus-time data to a model that describes the time-dependent profile of the spatially averaged temperature at the absorber’s back face similar to the designs of Myers and Herman (2002) and Wilkens (2002). This design was further improved with the addition of a thin copper sheet attached to the back of the absorber to facilitate rapid heat distribution.

An algorithm based on a least-squares analysis was developed and programmed into an Atmel microcontroller as part of an embedded system design that integrates the thermoacoustic sensor into a commercial ultrasound generator, SonaCell, developed by IntelligentNano (Edmonton, AB, Canada) (Wilkens 2002). This system can perform all the required computations, allowing the user to quickly and conveniently measure ultrasound intensities. This article outlines the design and characterization of a close-proximity thermoacoustic sensor using the SonaCell ultrasound system.

**DESIGN**

**Thermoacoustic sensor design**

The standard thermoacoustic sensor design comprises a solid cylinder surrounded by a second hollow cylinder, as shown in Figure 1 (left) (Fay and Rinker 1996b; Fay et al. 1994; Myers and Herman 2002; Wilkens 2002, 2010a, 2010b). At the sensor’s interface, a percentage of an incident ultrasound wave is reflected at the water-sensor boundary. Ignoring scattering effects, the remainder is transmitted into the absorbing material (Cheeke 2002). In a single reflecting approximation, the ultrasound beam is transmitted through the absorber and reflected at the back of the absorber, and then the beam propagates through the front face back to the water (Myers and Herman 2002). The attenuated ultrasound wave in the absorber will generate heat that travels to the back end of the inner cylinder toward a temperature-sensing unit, where a final temperature is recorded. This design is completely sealed to isolate the area where the temperature reading is taken from the influence of the outside room temperature.

Thermoacoustic sensors commonly use two methods of relating measured heat to ultrasound intensity: the sensor’s final equilibrium temperature (Fay et al. 1994; Wilkens 2010a, 2010b), and the sensor’s transient temperature over time (Myers and Herman 2002; Wilkens 2002). Each technique has its merits and is dependent on the physical design of the thermoacoustic sensor and the interaction between the sensor and the ultrasound transducer. The sensor’s final equilibrium temperature method, a commonly used method, has the merit of a simple measurement algorithm at the cost of a long equilibrium time. The sensor’s transient temperature method, on the other hand, has the merit of a short measurement time at the cost of a more complicated measurement algorithm.

In our setup, Figure 1 (right), the acoustic impedances of the ultrasound medium and sensor determine how much of the ultrasound wave is reflected at the medium-sensor interface and how much of the wave is transmitted. The “close proximity” nature of the sensor can cause its measurements to be affected by the ultrasound transducer’s self-heating effect, which occurs.
because of the energy lost in the conversion of electrical energy to mechanical energy. To mitigate these self-heating effects, our sensor design includes a medium such as ultrasound gel or degassed water (refer to Fig. 1 [right]). The medium can disperse the heat generated by the transducer during measurements and help to resolve the transducer’s self-heating effect on the sensor.

The ideal material for a thermoacoustic sensor combines perfect acoustic impedance matching with strong acoustic absorbance. Acoustic impedance \( Z \) is related to a material’s density \( \rho \) and acoustic velocity \( v \) (Ensminger 2009):

\[
Z = \rho \times v
\]  
(1)

Ultrasound waves are reflected at boundaries where there is a difference in acoustic impedance on each side; this is referred to as an impedance mismatch. A larger impedance mismatch will result in a higher percentage of the incident intensity being reflected \( (R_w) \) at the boundary:

\[
R_w = \left( \frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2 \times 100\%
\]  
(2)

\( Z_1 \) and \( Z_2 \) correspond to the acoustic impedance of the two materials at the boundary (Ensminger 2009). Neglecting scattering effects, the portion of the ultrasound wave that is not reflected at the boundary is transmitted through the material.

Plexiglass has been successfully used in previous investigations and is an available material that can be easily processed and quickly assembled in-house (Fay and Rinker 1996b; Wilkens 2002, 2004, 2010a). The inner absorbent cylinder in the sensor designed has a diameter of 20 mm and an absorber length of 2 mm. With the acoustic properties given in Table 1 and eqn (2), 13% of the incident ultrasound intensity will be reflected at the water-plexiglass interface. Ignoring scattering effects, 87% of the ultrasound wave will be transmitted into the plexiglass absorber. The low acoustic impedance of air, the insulating material, will cause 99% of the ultrasound wave to be reflected when it reaches the back of the sensor.

As it travels through the solid medium, the initial transmitted intensity is reduced as a result of acoustic attenuation. Acoustic attenuation is caused by the absorption and scattering of the ultrasound wave and is generally dependent on two factors: (i) the material through which the wave is transmitted and (ii) the frequency of the ultrasound (Ensminger 2009). The ultrasound intensity, after being attenuated over a distance \( x \), can be calculated using the equation

\[
I(x) = I_0 e^{-\mu x}
\]  
(3)

where \( I_0 = \) initial ultrasound intensity; and \( \mu = \) absorption coefficient.

Myers and Herman (2002) investigated transient temperature evaluation in a theoretical assessment. They followed the single-reflection theory and described a steady-state solution and a transient solution to the temperature rise averaged over the absorber’s cross section. They suggested that temperature data collected over time could be fit to a curve with the form

\[
T_{\text{ave}}(t) = \sum_{n=0}^{\infty} C_n (1 - e^{-\tau})
\]  
(4)

where

\[
C_n = \frac{I_0}{\mu k \pi (2n + 1)(\mu^2 l^2 + (2n + 1)^2 \pi^2)}
\]

and

\[
\tau = \frac{4l^2 \rho C_p}{\pi^2 k}
\]

In eqn (4), \( T_{\text{ave}}(t) = \) average temperature measured in the sensor in relationship to the temperature of the water bath; \( I_0 = \) incident ultrasound intensity; \( \mu = \) absorption coefficient; \( l = \) length of the absorber; \( k = \) thermal conductivity of the absorbing material; \( C_p = \) heat capacity of the material; and \( \rho = \) density of the material. Using this model, the ultrasound intensity can be inferred from the parameter \( C_n \).

The thermal properties of the thermoacoustic sensor will dictate how the thermal energy propagates through the sensor. We are interested in the heat diffusivity on the back face, where the thermistor is located. The solution to eqn (4) requires the temperature rise averaged across the back face. The goal of the sensor is to take accurate readings as quickly as possible; therefore, it is important for the temperature to rapidly spread across the back face. To investigate the diffusion of heat, we calculated the thermal diffusivity of various materials using the thermal properties outlined in Table 2 and the equation

\[
\alpha = \frac{k}{\rho C}
\]  
(5)

<table>
<thead>
<tr>
<th>Material</th>
<th>Density, ( \rho ) (kg/m(^3))</th>
<th>Acoustic velocity, ( v ) (m/s)</th>
<th>Acoustic impedance, ( Z ) (kg m(^2) s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plexiglass</td>
<td>1180</td>
<td>2700</td>
<td>3.19E6</td>
</tr>
<tr>
<td>Degassed water</td>
<td>1000</td>
<td>1484</td>
<td>1.48E6</td>
</tr>
<tr>
<td>Air</td>
<td>1.2041</td>
<td>343.26</td>
<td>413.3</td>
</tr>
</tbody>
</table>

Table 1. Acoustic properties of thermoacoustic sensor
The thermal diffusivity \((\alpha)\) expresses the rate at which a material transfers heat from one point to another and is related to the thermal conductivity \((k)\), density \((\rho)\) and heat capacity \((C)\) of the material.

Plexiglass has a thermal diffusivity of \(1.09 \times 10^{-2} \text{ m}^2/\text{s}\). Copper, a material with a high thermal conductivity, has a thermal diffusivity of \(1.18 \times 10^{-4} \text{ m}^2/\text{s}\), three orders of magnitude greater than that of plexiglass, allowing it to conduct heat at a much faster rate. A thin copper sheet (0.30 mm) was attached to the back face of the absorber using a thermal paste; this equally distributes the temperature across the whole surface faster than the plexiglass material. The temperature-sensing thermistor was placed on top of the copper layer. Care was taken to ensure that the copper did not short the thermistor leads.

**Thermoacoustic sensor hardware design**

The hardware of the thermoacoustic sensor consists of three main components: temperature sensing, processing and communication. The temperature sensing was done using an analogue-to-digital converter (ADC) in conjunction with a negative-temperature-coefficient thermistor to monitor the change in temperature at the back face of the absorber using a thermal paste; this equally distributes the temperature across the whole surface faster than the plexiglass material. The temperature-sensing thermistor was placed on top of the copper layer. Care was taken to ensure that the copper did not short the thermistor leads.

Thermistor calibration

After construction, the thermal response of the sensor was characterized. Thermal calibration was carried out by placing the sensor in a heated water bath and measuring the changes in the thermistor’s electrical resistance with respect to changes in temperature. A thermocouple with an accuracy of 0.1°C was attached to the sensor’s thermistor and employed to record temperature changes relative to the thermistor’s ADC readouts. In accordance with the operation of a negative-temperature-coefficient thermistor, the resistance decreased as temperature increased, as shown in Figure 2. There was a linear correlation between change in temperature and the ADC value.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity, (k) (W/(m*K))</th>
<th>Heat capacity, (C) (J/(kg*K))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plexiglass</td>
<td>0.167</td>
<td>1300</td>
</tr>
<tr>
<td>Copper</td>
<td>401</td>
<td>385</td>
</tr>
</tbody>
</table>

**Thermoacoustic sensor firmware design**

Temperature readings were taken using an oversampled ADC. Oversampling the ADC increases the resolution and reduces the noise of each reading. The ATmega324p microcontroller’s ADC has a 10-bit resolution. To measure the minimum changes in temperature caused by the ultrasound beam, we increased the resolution by 4 bits using oversampling techniques.

A least-squares equation was implemented to fit temperature-versus-time data to the equation described in eqn (6). The implemented least-squares algorithm was programmed in C onto an Atmel ATmega324p microcontroller. Every 0.1 s, temperature and time readings were taken and fit to eqn (4), and the coefficients were estimated. An iterative process with an experimentally determined \(R^2\) value of 0.000001 and step size of 0.001 was used.

**SENSOR CHARACTERIZATION**

**Thermistor characterization**

After construction, the thermal response of the sensor was characterized. Thermal calibration was carried out by placing the sensor in a heated water bath and measuring the changes in the thermistor’s electrical resistance with respect to changes in temperature. A thermocouple with an accuracy of 0.1°C was attached to the sensor’s thermistor and employed to record temperature changes relative to the thermistor’s ADC readouts. In accordance with the operation of a negative-temperature-coefficient thermistor, the resistance decreased as temperature increased, as shown in Figure 2. There was a linear correlation between change in temperature and the ADC value.
in resistance and temperature, with a coefficient of determination of 0.999 and the slope given in

\[ T = -0.01717X + 78.79 \]  

(8)

Here, \( X \) is the ADC readout. This relationship was programmed into the microcontroller operating the thermoacoustic sensor, allowing the sensor's temperature to be calculated.

**Transducer energy characterization**

The ratio of the power out of the transducer with respect to the power into the transducer, using the root mean squared voltage and current inputted into a piezoelectric transducer and measuring the output power with a radiation force balance, is

\[ \frac{P_{\text{out}}}{P_{\text{in}}} = 0.4519 \]  

(9)

Approximately 55% of the input energy is lost during the conversion of electrical energy to mechanical energy; a portion of this is due to the internal friction of the transducer, which results in thermal energy. In a close-proximity setup model, the heat produced by the transducer will influence temperature readings and measurement accuracy. A thin layer of ultrasound gel was originally used, and the self-heating effect of the transducer made the sensor's calibration and measurement highly dependent on the construction of the ultrasound transducer, as a transducer made out of a different material would generate a different amount of heat. Because of the heat produced by the transducer, we used degassed water as an ultrasound medium. The heat generated by the transducer is dispersed throughout the water and will not affect the sensor's readings.

**Figure 3** is a typical temperature-versus-time curve at intensity of 40 mW/cm². At time \( t = 0 \), the ultrasound generator was turned on and remained on throughout the whole process. The largest increase in temperature occurs between \( t = 0 \) s and \( t = 150 \) s, and the equilibrium temperature is not reached until \( t = 400 \) s. Therefore, an algorithm based on a transient equation describing the spatially averaged temperature across the back face of the sensor was needed.

**Transient temperature model analysis**

To evaluate the transient model with a thermoacoustic sensor implemented in a close-proximity setup, measured data were collected, and the least-squares model was used to fit the curve:

\[ T_{\text{ave}}(t) = C\left(1-e^{-t/T_{0}}\right)+T_{0}. \]  

(10)

Here, \( T_{\text{ave}} \) is the measured temperature averaged across the absorber's back face; and \( T_{0} \) is the starting temperature. The thermoacoustic sensor was coupled using degassed water in direct contact with the SonaCell ultrasound transducer. When the ultrasound generator was turned on, the thermoacoustic sensor began measuring the change in temperature at the absorber's back face. The temperature-versus-time curve with an incident ultrasound intensity of 80 mW/cm², for example, was measured. Using the least-squares method and the Curve Fitting Toolbox (MATLAB, Natick, MA, USA), the transient model was evaluated. The curve described in eqn (10) was fit to the measured data with prediction bounds with 95% certainty (calculated using the MATLAB Curve Fitting Toolbox) and is shown in **Figure 4**. The coefficients of the transient model are listed in

**Figure 4**. Temperature-versus-time data measured using the thermoacoustic sensor for an applied ultrasound intensity of 80 mW/cm². Data were fit with eqn (10) using the least-squares model with prediction bounds with 95% certainty at an ambient temperature of 24°C.
Table 3. Coefficients of the transient model for an applied ultrasound intensity of 80 mW/cm² at 24°C

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C$</td>
<td>$6.905 (6.813, 6.997)$ °C*</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$153.1 (148.9, 157.2)$ s</td>
</tr>
<tr>
<td>$T_0$</td>
<td>$24.09 (24.07, 24.11)$ °C</td>
</tr>
</tbody>
</table>

* 95% confidence bounds in parentheses.

Table 3. The 95% confidence bound indicates that the model is 95% confident that the mean value will fall between the upper and lower bounds. A smaller interval width is desirable because it indicates that in subsequent trials, the calculated coefficient values will be near the mean value determined by this curve fitting session.

The accuracy-of-fit analysis calculated by the MATLAB Curve Fitting Toolbox is outlined in Table 4. The sum of squares of residuals (SSE) value measures the total deviation between the measured data ($y$) and the predicted data ($\hat{y}$) calculated by the fitted curve:

$$\text{SSE} = \sum_{i=1}^{n} r_i^2 = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2$$  \hspace{1cm} (11)

The $R^2$ value is the square of the correlation between the measured data and the predicted value:

$$\text{SST} = \sum_{i=1}^{n} (y_i - \bar{y})^2$$

$$R^2 = 1 - \frac{\text{SSE}}{\text{SST}}$$  \hspace{1cm} (12)

SST is the sum of squares about the mean, where $\bar{y}$ is the overall mean. An $R^2$ value closer to 1 indicates that a great proportion of variance is accounted for by the model. Finally, the root mean squared error (RMSE) is an estimate of the standard deviation of the random component of the data. The RMSE is calculated as

$$\text{MSE} = \frac{\text{SSE}}{n}$$

$$\text{RMSE} = \sqrt{\text{MSE}}$$  \hspace{1cm} (13)

where $n$ is the number of terms. An RMSE value closer to 0 indicates that the model is more useful for prediction. After the MATLAB Curve Fitting Toolbox was used to analyze the goodness of fit of eqn (10) to the measured temperature-versus-time data collected when an 80 mW/cm² ultrasound intensity, for instance, was applied to the thermoacoustic sensor, we can conclude that the least-squares method does fit the curve to the measured data.

Substitution characterization

Acoustic calibration. Substitution calibration involves calibrating the ultrasound generator using a known calibration modality, in this case a radiation force balance, and then using the calibrated ultrasound generator to determine the relationship between the thermoacoustic sensor’s recorded temperature and the applied ultrasound. Four ultrasound transducers with surface areas of 3.5 cm² were operated at a 1.5-MHz frequency with a 20% duty cycle and 1-kHz pulse repetition frequency. The transducers, driven by a SonaCell ultrasound generator (IntelligentNano), were initially calibrated using a radiation force balance (Ohmic Instruments, Easton, MD, USA) at 40, 60, 80 and 100 mW/cm², respectively.

Experimental setup. The second measurement was carried out using the designed thermoacoustic sensor. The sensor was coupled directly to the transducer through the ultrasound medium, as shown in Figure 1 (right), and ultrasound was applied until a stable reading was obtained. This setup is easy to operate and different from various other experimental setups (Fay and Rinker 1996b; Fay et al. 1994; Wilkens 2002, 2004, 2010a, 2010b) using thermoacoustic sensors in which the sensor and the transducer are operated in a large degassed water bath.

RESULTS

Thermoacoustic sensor calibration

Using the procedure described above, we calibrated the thermoacoustic sensor using a radiation force balance and substitution calibration techniques, after the relationship between the thermoacoustic sensor’s recorded temperature and the ultrasound output intensity was determined. Figure 5 depicts the $C$ coefficient (in °C) calculated using the least-squares method to fit the curve described in eqn (10) to temperature data measured over time at different ultrasound intensities. A constant $\tau$ value, determined experimentally ($\tau = 130$ s), was used, and the ambient temperature, $T_0$, was measured before readings were taken. The data outlined in Figure 5 indicate that there is a linear relationship between the calculated $C$ coefficient and the applied ultrasound intensity, as suggested by eqn (10). The linear relationship (Fig. 5) between the applied ultrasound intensity ($I$) and the calculated $C$ coefficient is,
The $R^2$ value is 0.9962. This relationship is further analyzed and used to evaluate the thermoacoustic sensor’s ability to relate applied ultrasound intensity to measure temperature after 20 s.

**Effect of ambient temperature**

Operation of the thermoacoustic sensor relies on measuring the temperature changes produced by absorbed ultrasound waves. However, the sensor’s temperature changes depend not only on ultrasound intensity, but also on ambient temperatures. Although the thermistor in the sensor is insulated with air to eliminate the influence of outside room temperature, the front face of the sensor is still affected by the ambient temperature. The ambient temperature in our design is the temperature of the ultrasound medium shown in Figure 1 (right). If the effect of ambient temperatures is not taken into consideration, the measurement results would not be accurate and consistent. A range of ambient temperatures were measured to examine their effect on the value of the $C$ coefficient. Table 5 lists the $C$ values calculated at different starting ambient temperatures between 21°C and 26°C for the same ultrasound intensity, 60 mW/cm². The difference between the $C$ values at various starting temperatures indicates that there is a direct correlation between measured $C$ coefficient values and starting ambient temperatures. The data outlined in Figure 6 indicate linearity between measured $C$ coefficient values and starting ambient temperatures. The final version of the thermoacoustic sensor was calibrated using substitution calibration methods, which took the effect of ambient temperatures into consideration.

**Thermoacoustic sensor operation**

Using eqn (14) to relate the ultrasound intensity to the calculated $C$ coefficients determined from the measured temperature increases over time, we evaluated the performance of the calibrated thermoacoustic sensor. By comparing readings taken by a radiation force balance with readings taken using the calibrated thermoacoustic sensor, we examined the agreement between both techniques.

![Fig. 5. Linear relationship between applied ultrasound and the calculated $C$ coefficient at ambient temperature of 24°C.](image)

![Fig. 6. Linear relationship between starting ambient temperatures and the calculated $C$ coefficient under intensity of 60 mW/cm².](image)

![Fig. 7. Evaluation of the thermoacoustic sensor by comparison of measurements made with the thermoacoustic sensor with measurements taken using a radiation force balance. The linear line represents a 1:1 relationship between the radiation force balance and the thermoacoustic sensor.](image)

**Table 5. Calculated $C$ coefficients at various ambient temperatures**

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>$C$ value (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21.0</td>
<td>3.21</td>
</tr>
<tr>
<td>22.0</td>
<td>4.08</td>
</tr>
<tr>
<td>23.0</td>
<td>4.66</td>
</tr>
<tr>
<td>24.0</td>
<td>5.59</td>
</tr>
<tr>
<td>25.0</td>
<td>6.25</td>
</tr>
<tr>
<td>26.0</td>
<td>6.91</td>
</tr>
</tbody>
</table>
Six transducers were calibrated to nominal levels of 30, 40, 60, 80, 100 and 120 mW/cm² using a radiation force balance. The output intensity of the same transducers was then measured using the thermoacoustic sensor. This process simulates a new user taking a fresh reading every time, making it a practical evaluation of the thermoacoustic sensor’s operation. The result in Figure 7 indicates linearity between ultrasound intensity readings taken using a radiation force balance and measurements taken using the thermoacoustic sensor.

Table 6 outlines the measurements taken using the thermoacoustic sensor. Table 7 compares the measurements made by the radiation force balance and our thermoacoustic sensor. The thermoacoustic sensor had an output with an average error of 5.46% across 18 measurements.

**Effect of the back-face copper sheet**

Because readings taken by the thermoacoustic sensor are based on the temperature across the back face of the sensor, a thin copper sheet (0.30 mm thick) was attached to the plexiglass material with a thermal paste to distribute heat quickly and uniformly such that the temperature measured at one location can be assumed to be the average temperature across the entire back face. If there was not a uniform change in temperature, the goal would be to quickly distribute the heat from one location across the entire surface. Discrepancies between readings arise if the ultrasound energy heats an area away from the thermistor on a material with low thermal diffusivity.

Table 7. Comparison between measurements made using a radiation force balance and measurements made using a thermoacoustic sensor

<table>
<thead>
<tr>
<th>Radiation force balance</th>
<th>Thermoacoustic sensor</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 30.14</td>
<td>28.01</td>
<td>7.07</td>
</tr>
<tr>
<td>2 40.28</td>
<td>37.37</td>
<td>7.22</td>
</tr>
<tr>
<td>3 59.09</td>
<td>60.32</td>
<td>2.08</td>
</tr>
<tr>
<td>4 80.58</td>
<td>85.76</td>
<td>6.43</td>
</tr>
<tr>
<td>5 100.25</td>
<td>105.51</td>
<td>5.25</td>
</tr>
<tr>
<td>6 120.73</td>
<td>126.43</td>
<td>4.72</td>
</tr>
</tbody>
</table>

As seen in Table 8, the average standard deviation when the transducer is placed in different locations on the copper-backed sensor is 58.2% less than the average standard deviation of the sensor without the copper back. This is due to the higher thermal diffusivity of copper compared with the plexiglass material, allowing...
the temperature to dissipate across the back face more evenly.

The results in Figure 8(a) clearly illustrate why the sensor without copper backing cannot yield accurate results. At the same starting temperature, the calculated \( C \) coefficients must be close to the same value at every reading. This is especially important because substitution calibration methods are used. Once the sensor is calibrated, the same \( C \) coefficient that correlates to a specific ultrasound intensity should be generated every time that particular ultrasound intensity is applied. Conversely, the results in Figure 8(b) indicate that the sensor with the copper backing can generate more consistent results. The algorithm implemented requires that measurements be taken using the average temperature across the absorber’s back face. To record the average temperature, multiple sensors or a high-conductivity surface must be used to rapidly distribute heat across the back face (Myers and Herman 2002).

**DISCUSSION**

A low-cost and easy-to-operate ultrasound power sensor was designed, tested and implemented. Embedded system functions were realized using an Atmel microcontroller and integrated with the SonaCell ultrasound generator. A close-proximity setup was removing the necessity to suspend the sensor and transducer in a large water tank. This thermoacoustic sensor offers a convenient alternative to radiation force balance-based methods for determining ultrasound output intensity. However, the drawback is that thorough calibration using the transducer is needed beforehand. In this article, we have specifically described the use of a prototype design to measure ultrasound intensity of transducers operating at 1.5-MHz frequency in intensity ranges appropriate for LIPUS biology experiments using the ultrasound transducer from the SonaCell ultrasound generator. Measurement examples reveal a direct correlation between the average temperature on the back face of the sensor and the applied ultrasound intensity. Substitution calibrations using a radiation force balance were performed to determine the relationship between ultrasound intensity and the \( C \) coefficient from eqn (10). This relationship yielded a linear equation used to correlate the calculated \( C \) coefficients with ultrasound intensity. Good agreement was found between the thermoacoustic sensor and radiation force balance. Because of the linearity observed, it is expected that the sensor can measure intensities even greater than 120 mW/cm\(^2\).

Error and consistency are two important criteria determining the usefulness and practicality of a sensor. Standard radiation force balances measure low-megahertz frequency ranges and power ranges within 100 mW. With the use of absorbing and reflecting targets, measurement uncertainties in the range of \( \pm 7\% \) were achieved (Shaw and Hodnett 2008). The substitution calibration methods used will link the thermoacoustic sensor’s error to the radiation force balance’s uncertainty. Additionally, the single-reflection approximation, sound field geometry or position of the sensor and transducer, as well as the noise in the system, contribute to thermoacoustic sensor error.

Because of the convenience of thermistor attachment, temperature measurements are made at the absorber’s back face. In this case, if the ratio of the absorber’s radius to the beam radius is less than one, calculations assuming uniform heating will yield inaccurate results if measurements are made at a single back-face location. To implement an algorithm that requires measurements to be made using the average temperature across the absorber’s back face, one or more of the following must be taken into consideration: the ultrasound beam radius must be the equal to 100\% of the absorber radius, multiple sensors must be implemented or a high-conductivity surface must be used to rapidly distribute heat across the back face (Myers and Herman 2002). In this case, a thin copper sheet with high thermal diffusivity was implemented. Table 8 outlines the effect the copper sheet had on \( C \) coefficient calculations, which depends on an averaged temperature across the back face of the sensor. From these results, we can conclude that regardless of the position of the ultrasound transducer, the copper layer averages the temperature across the entire back face more efficiently than plexiglass alone.

Accurate performance of the sensor requires the slope of the ultrasound intensity versus \( C \) value to be consistent across trials. As seen in Figure 8(b), the copper-backed thermoacoustic sensor performed well in measuring ultrasound intensities; for example, it maintained a similar slope between readings. Results from the same experiment carried out with the thermoacoustic sensor without the copper layer are illustrated in Figure 8(a). The average standard deviation of the copper-backed sensor is 58.2\% less than the average standard deviation of the sensor without the copper back. The copper layer reduces the fluctuation between readings by quickly distributing the temperature across the entire back face.

In the future, we will investigate ways to further reduce sensing errors. The physical design or material can be adjusted to completely absorb the ultrasound wave before it reaches the front face after the first reflection at the back face. Presently, 13\% of the ultrasound wave will be reflected back into the thermoacoustic sensor after it has traveled once through the plexiglass cylinder. Another issue is the portion of the wave that is transmitted out of the sensor back to the transducer. These
problems can be avoided by placing an absorbing layer on the back face of the sensor to completely absorb the transmitted ultrasound wave. Other means of improvement include reducing the sensor’s response time and minimizing the variance between readings.

CONCLUSIONS

Although the current method of using a radiation force balance to calibrate ultrasound intensity is the gold standard, its setup is complex and may not be justified in many cases. In this article, we proposed a close-proximity thermoacoustic sensor design mechanism. To reduce the design concept to practice, we characterized, tested and implemented a sensor to work with the Sona-Cell ultrasound generator. The biggest advantage over the radiation force balance is its ability to make measurements in the field (i.e., during equipment service activities). Compared with thermoacoustic sensor designs outlined in the literature and in patents, the design described in this article has several novel components. The implementation of a thin metal layer increases heat conduction at the back of the absorber. The metal layer also reduces the dependence of the ultrasound transducer’s focal point. The results indicate that the copper layer can increase heat diffusion 1000-fold compared with plexiglass alone and reduce the sensor’s error. No other sensor described in the literature uses a sensor in contact with an ultrasound transducer to measure ultrasound intensity. The setup is more convenient than previously described setups that require the sensor and transducer to be placed in a large water bath. Finally, an embedded system design using a microcontroller running a least-squares algorithm was implemented to process the data in real time.

Although thermoacoustic sensors are unlikely to replace the industry standard for ultrasound calibration, the results describe in this article indicate that close-proximity thermoacoustic sensors provide a convenient modality to quickly verify ultrasound intensity without any complicated setup. Furthermore, the embedded system design will allow for future integration with ultrasound generators, such as an integrated ultrasound auto-calibration system or real-time analysis of ultrasound propagation.

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