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Developing a Thermoacoustic Sensor Adaptive to Ambient Temperatures

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Abstract—**In this paper, a simple and adaptive thermoacoustic sensor was designed to measure Low Intensity Pulsed Ultrasound (LIPUS). Compared to other thermoacoustic sensor designs, our novelty lies in (i) integrating an ultrasound medium layer during the measurement to simplify the complicated set-up procedures and (ii) taking the effect of ambient temperatures into design consideration. After measuring temperature increases with various ambient temperatures under different ultrasound intensities, a relationship among ultrasound intensities, ambient temperatures and coefficients of temporal temperature changes was calculated. Our improved design has made the sensor easy to operate and its performance more accurate and consistent than the thermoacoustic sensor designs without considering ambient temperatures. In all, our improved design greatly enhances the thermoacoustic sensor in practical ultrasound calibration.**

I. INTRODUCTION

In therapeutic ultrasound design, accurate control of the spatial average temporal average intensity (I_{sata}) is important, since the physiological effects of therapeutic ultrasound highly depend on the intensity and duration of applications [1]. Therefore, it is necessary to design a sensor that can accurately measure the intensity of the ultrasound device (The intensity used in the remaining of the paper refers to I_{sata}). Currently, there are two conventional and commonly used techniques to evaluate ultrasound output parameters: hydrophones and radiation force balances. While the hydrophones can output acoustic pressure time waveform, the intensity is estimated by assuming the plane-wave of the acoustic field [2]. This assumption, however, is invalid in transducer near-field [3]. The radiation force balance is limited by its strong dependence on the ultrasound wave's geometry and affected by background vibrations [3,4]. Compared to previously mentioned techniques, thermoacoustic sensing, as a very simple and low-cost technique, has its own advantages and the potential to be an alternative approach to determine ultrasound intensity.

Although the concept of thermoacoustic sensors based on thermal measuring methods is not new, the novelty lies on how to use this method to measure Low Intensity Pulsed Ultrasound and design thermoacoustic sensors that are easy-to-operate and self-adaptive to the ambient temperatures. The set-up procedures for previous thermoacoustic sensors are very complicated, which require the sensor and transducer to be placed in a large water tank, similar to hydrophone or radiation force balance measurements [5,6]. Our design, on the other hand, does not require any complicated set-up procedures, and is very convenient to use. Our close-proximity thermoacoustic sensor with an ultrasound medium layer can provide an easy way to measure ultrasound intensity through directly coupling with a transducer. The thermoacoustic sensor measures the temperature changes caused by incident ultrasound energy to determine the ultrasound intensity. However, the sensor's temperature changes depend not only on the ultrasound intensity, but also on ambient temperatures. Therefore, overcoming the effect of various ambient temperatures becomes critical for the improved design to enhance the thermoacoustic sensor's accuracy and consistency. To our best knowledge, no paper about the thermoacoustic sensor design considering ambient conditions has been published.

This remaining paper will focus on the design, calibration and test of the thermoacoustic sensor.

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II. THERMOACOUSTIC SENSOR DESIGN

The thermoacoustic sensor is shown in Fig. 1. A small compartment with an absorbing cylinder underneath is designed to hold a layer of ultrasound medium (degassed water). The absorbing cylinder can attenuate ultrasonic wave to transform ultrasonic energy into heat. A thermistor is fixed at the center of the absorber as a temperature probe to measure temperature changes. The temperature increases are measured by the thermistor and sent to a microcontroller for recording and processing. The thermistor is sealed in the sensor to remove the influence from outside. As a proven material in previous design [5-7], plexiglass was chosen as absorbing material in this thermoacoustic sensor design, which achieves good acoustic impedance matching with strong acoustic absorbance [5].

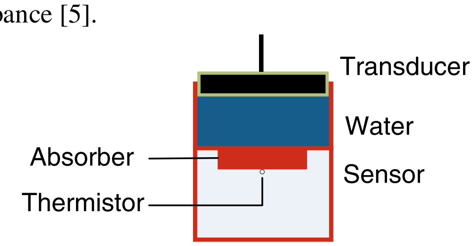

Figure 1. The structure of the thermoacoustic sensor

The advantage of a close-proximity setup over the conventional sensor is its simplicity; in particular, no large water tank is required. The temperature of the transducer rises during the measurement due to energy lost in the conversion from electrical energy to mechanical energy, which can affect the measurement accuracy in the close-proximity setup. A very thin layer of ultrasound gel was originally used as ultrasound medium and the self-heating effect of the transducer still affected the accuracy of the sensor. The degassed water in Figure 1 works not only as coupling medium, but also as a buffer, and heat generated by the transducer is dispersed throughout the water and will not affect the readings of thermoacoustic sensor.

III. Effect of Ambient Temperatures on Sensor Operation

The principle of the thermoacoustic sensor's operation is based on measuring heat transformed and generated by incident ultrasonic energy [5]. Through the measurement of temperature increases due to heat, the ultrasound intensity can be determined by fitting transient temperature model [6]. However, the ultrasound intensity is not the only factor that determines the curve of the sensor's temperature changes, because ambient temperatures can also affect the measurement results. Although the thermistor in the sensor is insulated with air to remove the influence from the outside 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 degassed water. With different starting ambient temperatures, the temperature curves of the sensor are not the same even when the incident ultrasound intensity is the same. Fig. 2 shows two temperature curves with different ambient temperatures under the same intensity of 100mW/cm^2. Large differences can be observed from the figure. One temperature curve under ambient temperature of 22.0°C started at 24.4°C and ended at 30.8°C with an increment of 6.4°C in 20 seconds; the other curve under ambient temperature of 24.0°C started at 24.4°C and ended at 31.5°C with an increment of 7.1°C in 20 seconds. From these results, we can see the ambient temperatures can significantly impact the final reading.

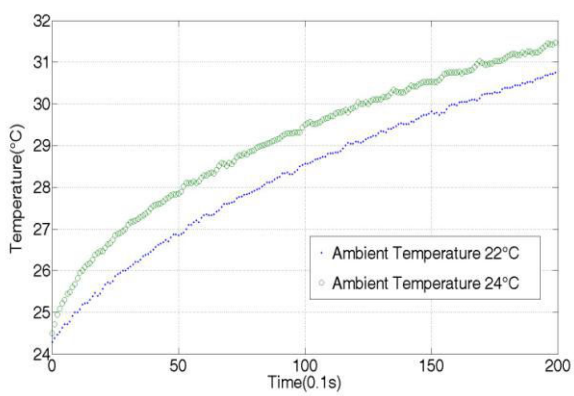

Figure 2. The sensor's temperature curves at ambient temperature 22 °C and 24 °C under the same ultrasound intensity 100 mW/cm^2

IV. Sensor Calibration and Algorithm Design

A. Sensor Calibration

A. 1 Thermistor Calibration

The first step to calibrate the sensor is the thermistor calibration. The purpose of thermistor calibration is to find the relationship between the sensor's temperature and the thermistor's readout. The thermistor readout is the voltage drop of the thermistor with a constant current, and the ADC readout is the digital number converted from the analog voltage through microcontroller's analog to digital converter (ADC). The process was carried out in a heated water bath. A thermocouple with an accuracy of 0.1°C was employed to record temperature changes relative to the thermistor's ADC readouts. A linear relationship is found between the changes in the ADC readouts and temperatures as shown in Fig. 3.

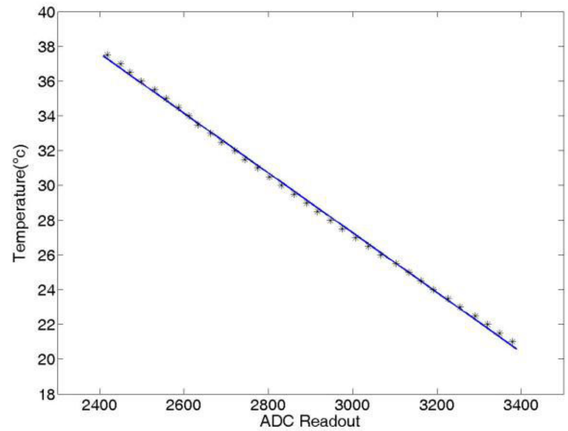

Figure 3. Thermistor linear calibration line between the temperatures and ADC readouts

The linear relationship is shown in equation (1).

$$T = -0.0167 \times X + 77.224 \quad (1)$$

where T is the temperature and X is the ADC readout.

After thermistor calibration, the thermistor can be employed to record temperature changes when ultrasound is applied. Since the accurate record of the sensor's temperature curves influences the final measurement accuracy of ultrasound intensity, instead of recording temperature increases every second, the temperature increases were recorded every 0.1 seconds to increase the resolution. Meanwhile, the oversampling technique is used to increase the ADC resolution and reduces the noise of each reading [7].

A. 2 Substitution Calibration

The substitution calibration was implemented after thermistor calibration. First, an ultrasound measurement device was employed to calibrate the ultrasound generator device (1.5 MHz frequency, 20% duty cycle) to a fixed intensity. The ultrasound generator device was then applied to the thermoacoustic sensor to find the relationship between the sensor's temperature increases and applied ultrasound intensities. An ultrasound power meter was used as the substitute ultrasound measurement device in this design.

An ultrasound generator system was calibrated to intensities of 40, 60, 80 and 100 mW/cm^2. Under the above intensities, the sensor's temperature changes with various ambient temperatures were recorded respectively.

B. Curve Fitting Based on the Transient Model

After the sensor's temperature increases have been recorded with various ambient temperatures under different intensities, it is vital for the sensor to relate the temperature curves to applied ultrasound intensities. Curve fitting based on the transient model can abstract parameters that represent the trend in temperature changes. Relating the parameters to applied ultrasound intensities enables the sensor to detect applied ultrasound intensities after calibration. Curve fitting can be implemented based on the transient model as suggested in [6]. The least squares fitting method was used during the process of curve fitting to find the optimum fitting curve by minimizing the sum of squared errors. The transient model can be expressed as equation (2).

$$T(t) = T_0 + C\left(1 - e^{\frac{-t}{\tau}}\right) \quad (2)$$

where T(t) is the measured temperature of the absorbing cylinder's back face, T_0 is the starting temperature, C is the coefficient related to the ultrasound intensity and temperature increasing trend, and τ is time constant and can be determined during curve fitting procedure.

MATLAB's curve fitting toolbox was used to evaluate the curve fitting based on the measured data. Fig. 4 shows the curve fitting result for the sensor's temperature increases under intensity of 80 mW/cm^2 with 95% certainty of prediction bounds by MATLAB. Table I shows the coefficients of the curve fitting result.

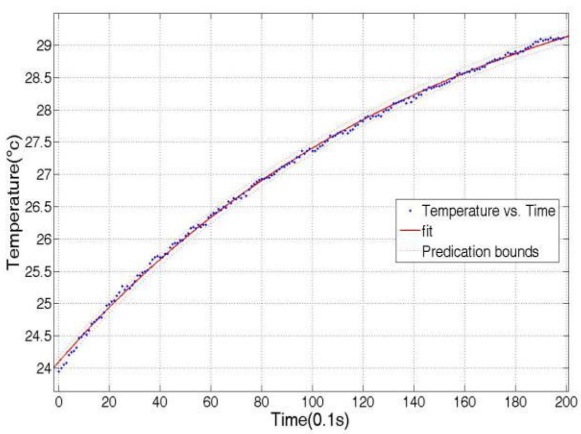

Figure 4. The curve fitting result to the sensor's temperature increases under intensity of 80 mW/cm^2

TABLE I
COEFFICIENTS OF THE TRANSIENT MODEL FOR AN APPLIED ULTRASOUND INTENSITY OF 80 MW/CM^2 AT 24 °C

Ultrasound Intensity [mW/cm^2]	Coefficient C (95% ConfidenceBounds) [°C]	Coefficient τ (95% Confidence Bounds) [sec]	Coefficient T_0 (95% Confidence Bounds) [°C]
80	6.905 (6.813, 6.997)	153.1 (148.9,157.2)	24.09 (24.07, 24.11)

Based on the least squares curve-fitting method, a series of parameters C and τ can be derived. Since the value of τ also influences the value of C during the curve fitting procedure, a fixed τ must be chosen to do the curve fitting to get a series of correlated C values. After trying a range of derived parameters τ, the result based on τ=130 was optimum. The values of the coefficient C under different intensities with various starting ambient temperatures are determined based on the curve fitting. Fig. 5 shows the linear relationship between the calculated C coefficient and the applied ultrasound intensity at ambient temperature 24.0°C.

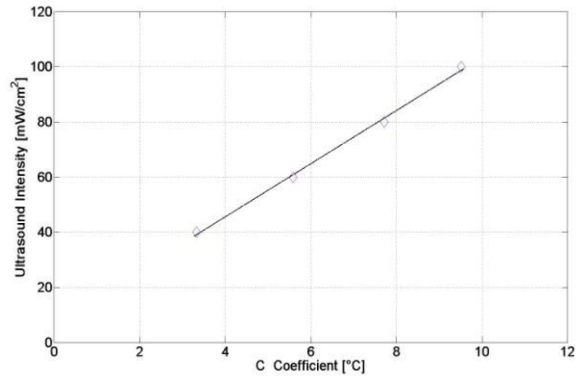

Figure 5: Linear relationship between applied ultrasound and the calculated C coefficient at ambient temperature of 24°C.

Equation (3) is the linear fitting equation

$$I = 9.637 \times C + 6.973 \quad (3)$$

C. Thermoacoustic Sensor Algorithm

After determining a series of correlated C values at certain ultrasound intensities and ambient temperatures, the next step is to make the sensor recognize arbitrary ultrasound intensity at a random ambient temperature based on the calculated C values. The linear fitting was carried out under different intensities to find the influence of the ambient temperatures to the value of the coefficient C. Fig.6 shows the relationship between starting ambient temperatures and parameter C values under intensity of 60 mW/cm^2.

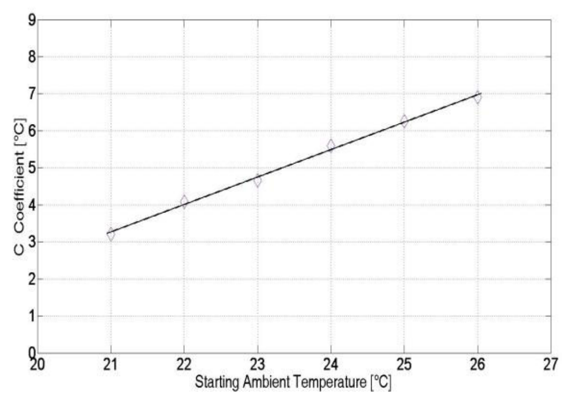

Figure 6. Linear relationship between starting temperatures and parameter C values under intensities of 60 mW/cm^2

From the figure above, we can see a good linearity between starting ambient temperature and C value for the intensity.

Equation (4), (5), (6) and (7) are the linear fitting equation for ultrasound intensity 100, 80, 60 and 40 mW/cm^2 respectively.

$$C_1 = 0.714 \times T - 7.67 \quad (4)$$

$$C_2 = 0.767 \times T - 10.75 \quad (5)$$

$$C_3 = 0.747 \times T - 12.44 \quad (6)$$

$$C_4 = 0.569 \times T - 10.40 \quad (7)$$

After the calibration, an algorithm was designed to realize the function of the thermoacoustic sensor. When ultrasound is applied, there will be obvious temperature increases in the sensor, and the temperature before the obvious changing is recorded as the starting ambient temperature. With the given starting ambient temperature, the equations (4), (5), (6) and (7) can be used to calculate the values of C_1, C_2, C_3 and C_4, which correspond to ultrasound intensities of 100, 80, 60 and 40mW/cm^2 respectively. The coefficient C related to the applied ultrasound intensity can be calculated through curve fitting to the temperature data. After determining the value of C, the values of C_1, C_2, C_3 and C_4 are used to compare with C to get two close parameters. Through interpolation or extrapolation based on the two close parameters and their correlated ultrasound intensities, the applied ultrasound intensity related to C can be evaluated. The thermoacoutic sensor algorithm flowchart is shown in Fig. 7

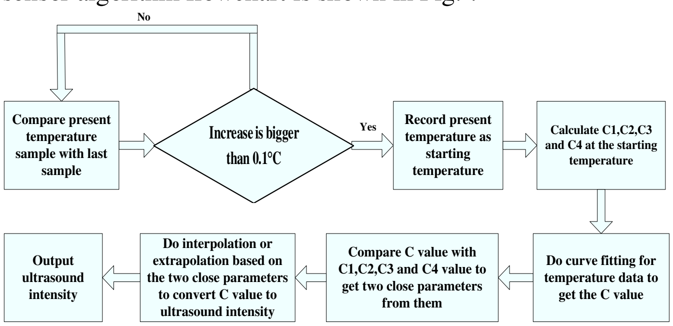

Figure 7. The thermoacoustic sensor's algorithm flowchart

V. RESULTS

The thermoacoustic sensor can detect ultrasound intensity within 20 seconds. Three separate measurements were performed under different intensities at different ambient temperature as shown in Table II. To evaluate the performance of the adaptive thermoacoustic sensor, the same measurements were also performed by the thermoacoustic sensor without considering the effect of ambient temperatures for comparison, which is shown in Table III (The sensor was only calibrated at ambient temperature of 22.0°C).The average of both measurement results were calculated. By comparing the measurement results of standard ultrasound power meter with both types of thermoacoustic sensors, errors of their measurement results were also calculated. A comparison was shown in Table IV.

TABLE II
MEASUREMENT RESULTS OF THE ADAPTIVE THERMORACOUSTIC SENSOR

	Ambient Temperature:22°C	Ambient Temperature:23°C	Ambient Temperature:24°C
1	37.38 mW/cm^2	36.94 mW/cm^2	37.80 mW/cm^2
2	58.48 mW/cm^2	59.59 mW/cm^2	62.90 mW/cm^2
3	86.11 mW/cm^2	85.40 mW/cm^2	85.76 mW/cm^2
4	105.01 mW/cm^2	105.86 mW/cm^2	105.65 mW/cm^2

TABLE III
MEASUREMENT RESULTS OF THE THERMORACOUSTIC SENSOR WITHOUT AMBIENT TEMPERATURE ALGORITHM

	Ambient Temperature:22°C	Ambient Temperature:23°C	Ambient Temperature:24°C
1	41.75 mW/cm^2	45.67 mW/cm^2	50.73 mW/cm^2
2	60.38 mW/cm^2	64.94 mW/cm^2	74.07 mW/cm^2
3	78.62 mW/cm^2	86.87 mW/cm^2	96.63 mW/cm^2
4	103.61 mW/cm^2	111.48 mW/cm^2	121.83 mW/cm^2

TABLE IV
THE COMPARISON OF MEASUREMENT RESULTS

Ultrasound Power Meter	Adaptive Thermoacoustic Sensor	Errors	Normal Thermoacoustic Sensor	Errors
40 mW/cm^2	37.37 mW/cm^2	6.58%	46.05 mW/cm^2	15.58%
60 mW/cm^2	60.32 mW/cm^2	0.53%	66.46 mW/cm^2	10.77%
80 mW/cm^2	85.76 mW/cm^2	7.20%	87.37 mW/cm^2	9.21%
100 mW/cm^2	105.51 mW/cm^2	5.51%	112.31 mW/cm^2	12.31%

From the table above, we can see that, compared to standard ultrasound power meter, the adaptive thermoacoustic sensor's errors are within 8% at different ambient temperatures, while the errors of the thermoacoustic sensor without considering the effect of ambient temperatures are within 16%. The maximum standard deviation of the adaptive sensor’s measurement results under different intensities is 2.30 mW/cm^2, while it is 9.14 mW/cm^2 for the sensor without considering the effect of ambient temperatures, which indicates the performance of the adaptive thermoacoustic sensor is much more consistent at various ambient temperatures.

VI. CONCLUSION

Although the radiation force balance is the gold standard for measuring ultrasound intensity, it is not possible for real-time monitoring in certain settings, for example bioreactors, or in clinic to measure ultrasound intensities during treatment. Foreseeing these needs, we have proposed a close-proximity thermoacoustic sensor in this paper. Calibration and curve fitting were performed to find the relationship among temperature curve coefficient C values, different ultrasound intensities and various starting ambient temperatures. The sensor was designed to measure Low Intensity Pulsed Ultrasound (LIPUS) within 100mW. The test results show that the adaptive thermoacoustic sensor is adaptive to the various ambient temperatures and has an error within 8% compared to the ultrasound power meter, and the maximum standard deviation is 2.30 mW/cm^2 at various temperatures. The improved design has made the thermoacoustic sensor more practical for real life applications.

REFERENCES

[1] P.A. Artho, J.G. Thyne, B.P. Warring, C.D. Willis, J. Brismée and N.S. Latman, "A calibration study of therapeutic ultrasound units", *Physical Therapy*, vol. 82, pp. 257-263, 03. 2002.

[2] K. Beissner, "On the plane-wave approximation of acoustic intensity", *J.Acoust.Soc.Am.* vol. 71, pp. 1406, 06/02. 1982.

[3] B. Zeqiri, Gordana Žauhar, M. Hodnett and J. Barrie, "Progress in developing a thermal method for measuring the output power of medical ultrasound transducers that exploits the pyroelectric effect", *Ultrasonics*, vol. 51, pp. 420-424, 2011.

[4] A. Shaw and M. Hodnett, "Calibration and measurement issues for therapeutic ultrasound", *Ultrasonics*, vol. 48, pp. 234-252, 2011.

[5] V. Wilkens, "A thermal technique for local ultrasound intensity measurement: part 1. Sensor concept and prototype calibration", *Measurement Science and Technology*, vol. 21 , 2010.

[6] V. Wilkens, "Thermoacoustic ultrasound power measurement using evaluation of transient temperature profiles", *Ultrasonics Symposium*, vol. 2, pp. 1399-1402, 2002.

[7] M.Choi, W.Ang and J Chen, "Close-proximity, real-time thermoacoustic sensors: design, characterization and testing", *The IEEE International Symposium on Circuits and Systems*, 2012.