ACCURATE TEMPERATURE ESTIMATION IN ULTRASONIC PULSE-ECHO SYSTEMS

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Abstract

Ultrasonic pulse-echo systems are widely used to estimate properties of liquids and gases. A common principle is to use a buffer material (buffer-rod) fixed to the ultrasound transducer. Assuming the acoustic properties of the buffer-rod are known, it is then possible to calculate the acoustic impedance of the unknown material.

A problem occurs if the temperature of the buffer-rod changes during the measurements, since the properties of the buffer-rod, such as the acoustic attenuation depends on temperature. If, however, the temperature is recognized, it is possible to compensate for this.

In this paper we present a method based on speed of sound changes in the buffer-rod to estimate the temperature. With the resulting model we are able to estimate temperatures in PMMA for the interval 5 °C to 60 °C with a 0.1 °C accuracy (at a 95% confidence level).

Introduction

This paper deals with problems encountered when a buffer-rod pulse-echo setup is used to measure the speed of sound in, and specific acoustic impedance [1] of an unknown medium. The principle was first described by Lynnworth [2] and Papadakis [3], and later further developed by Püttmer [4] and Deventer [5] for density measurement of liquids. The setup investigated in this paper was developed to measure the acoustic impedance and speed of sound in an injectable bone substitute. The purpose is to monitor changes of acoustic properties as a function of the setting time of the material. This allows the supervision of the entire setting process on-line. This idea was first presented by Carlson *et al.* in [6].

There are many alternative designs of such density probes, but the working principle is the same for all of them. A reference material, for which the acoustic properties (e.g. specific acoustic impedance and speed of sound) are known. When the sound pulse encounters the boundary between this known material and the unknown medium being investigated, part of the pulse is reflected, and the rest is transmitted. The reflection coefficient depends on differences in acoustic impedance between the two media, as

$$R_{12} = \frac{z_2 - z_1}{z_2 + z_1} = \frac{\rho_2 c_2 - \rho_1 c_1}{\rho_2 c_2 + \rho_1 c_1}, \tag{1}$$

where z_1 and z_2 are the specific acoustic impedances of medium 1 and 2, respectively, while ρ_1, ρ_2 and c_1, c_2 are the corresponding densities and sound velocities.

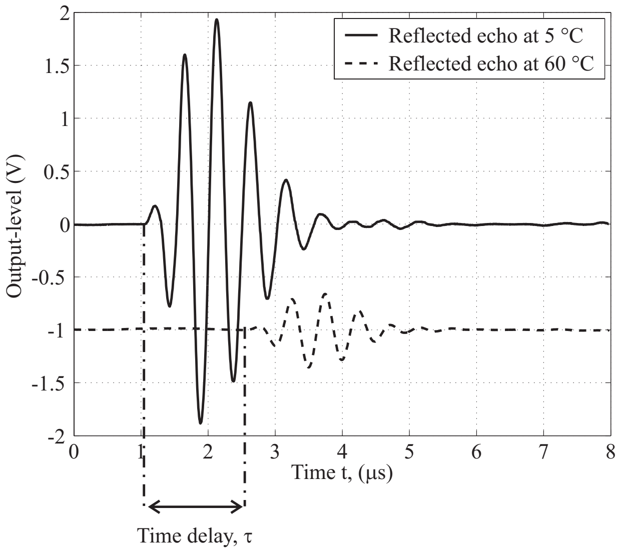

Figure 1 : Two echoes coming from the interface between a PMMA buffer-rod and water, at 5 °C and 60 °C. It is clear that both the arrival time and amplitude of the echoes change with temperature.

The common assumption with all pulse-echo techniques is that the acoustic properties of the buffer-rod material are known. This is often the case, as long as one can assume that the temperature is known or kept constant, at a level where these properties have been determined. If, however, the temperature of the buffer-rod changes during the measurements, properties like acoustic impedance, speed of sound and acoustic attenuation will also change. Fig. 1 illustrates this for a PMMA (polymethylmethacrylate, or Plexiglas) buffer-rod. A temperature change from 5 °C to 60 °C causes both a change in sound velocity, and attenuation. The attenuation change is a problem, while the time delay gives an indication of the temperature change. The underlying assumption is that the change in transducer efficiency is minimal or considered as part of the buffer-rod characteristics.

In this paper we show how the time-delay in Fig. 1 can be used to compensate for losses caused by temperature changes.

Experimental setup

Fig. 2 shows the experimental setup used in this paper. The probe consists of an ultrasound transducer with

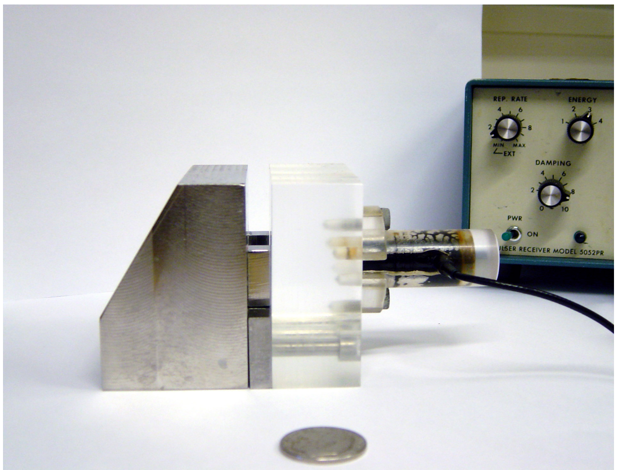

Figure 2 : Pulse-echo setup used in the measurements.

center frequency of 2 MHz and a diameter of 14 mm, manufactured by *Ceram AB*. The transducer was fixed to a 25 mm thick PMMA buffer-rod, and a back reflector of stainless steel. The transducer was excited using a *Panametrics 5025PR* pulser/receiver. The transducer and the buffer-rod were immersed in water and put into a temperature controlled chamber (*Heraeus Vötsch HT4010*). The temperature chamber was set to the requested value and the temperature was then stabilized for twelve hours. Once the temperature had stabilized, 100 pulses were collected using a Nicolet 460 digitizing oscilloscope, sampling at 200 MHz with a vertical resolution of 8 bits. For each pulse, the temperature was measured using a PT100 sensor connected to a *Systemteknik Thermolyzer*.

Theory

In this section, we first describe the principle of the density probe and temperature estimation. We show how this can be used to compensate for acoustic losses in the buffer-rod material. Finally, the uncertainty of the method is evaluated.

The density probe

The density probe used in this paper was first used in [6]. Fig. 3 shows the operating principle. Two echoes are recorded: One from the PMMA/sample interface and the other from the back reflector. The time delay between the two gives the speed of sound through the sample, since the thickness of the sample is known at 20 °C. The amplitude of the first echo, and the amplitude of a calibration measurement with a water sample, gives the acoustic impedance, z_2, of the sample, as

$$z_2 = \frac{1+R_{12}}{1-R_{12}} z_1, \qquad (2)$$

where the reflection coefficient R_{12} is given by

$$R_{12} = \frac{A_1}{A_w} R_{1,w}, \qquad (3)$$

where A_1 is the measured amplitude of the PMMA/sample echo, A_w is the corresponding amplitude from the calibration measurement, and $R_{1,w}$ is the known reflection coefficient between PMMA and water. After this calibration, the settings of the electronics are kept constant.

Temperature estimation

When the temperature in the buffer-rod material changes, it affects both the speed of sound and the geometrical dimensions of the buffer-rod sample. Because of this, the time it takes for a pulse to travel back and forth trough the buffer-rod will change. Defining the time-delay τ, to be the difference in propagation time caused by a temperature change $\Delta T = T - T_0$, where T_0 is the calibration temperature. The time delay is estimated using a standard cross-correlation technique, in combination with the sub-sample estimator in [9].

We assume that the temperature can be estimated as a polynomial function of the time-delay, τ

$$T = f(\tau) = \beta_0 + \sum_{n=1}^{N} \beta_n \tau^n + \varepsilon, \qquad (4)$$

where ε denotes the model error and N is the model order (*i.e.* the degree of the polynomial to be fitted to the data). Given a number of measurements, at M different temperatures, this can be written in matrix notation as

$$\begin{bmatrix} T_1 \\ T_2 \\ \vdots \\ T_M \end{bmatrix} = \begin{bmatrix} 1 & \tau_1 & \cdots & \tau_1^N \\ 1 & \tau_2 & \cdots & \tau_2^N \\ 1 & \vdots & \ddots & \vdots \\ 1 & \tau_M & \cdots & \tau_M^N \end{bmatrix} \begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_N \end{bmatrix} + \boldsymbol{\varepsilon}$$
$$\mathbf{T} = \boldsymbol{\tau} \cdot \boldsymbol{\beta} + \boldsymbol{\varepsilon}. \qquad (5)$$

The model coefficients $\boldsymbol{\beta}$ are then estimated as the least-squares fit of the polynomial to the measured data, that is

$$\hat{\boldsymbol{\beta}} = (\boldsymbol{\tau}^T \boldsymbol{\tau})^{-1} \boldsymbol{\tau}^T \cdot \mathbf{T}. \qquad (6)$$

For a given time-delay, the estimated temperature then becomes

$$\hat{T} = \hat{\beta}_0 + \sum_{n=1}^{N} \hat{\beta}_n \tau^n. \qquad (7)$$

For the experiments with a PMMA buffer-rod, we found a second order polynomial to be sufficient for temperatures in the interval 5 °C to 60 °C, that is Eq. (7) simplifies to

$$\hat{T} = \hat{\beta}_0 + \hat{\beta}_1 \tau + \hat{\beta}_2 \tau^2. \qquad (8)$$

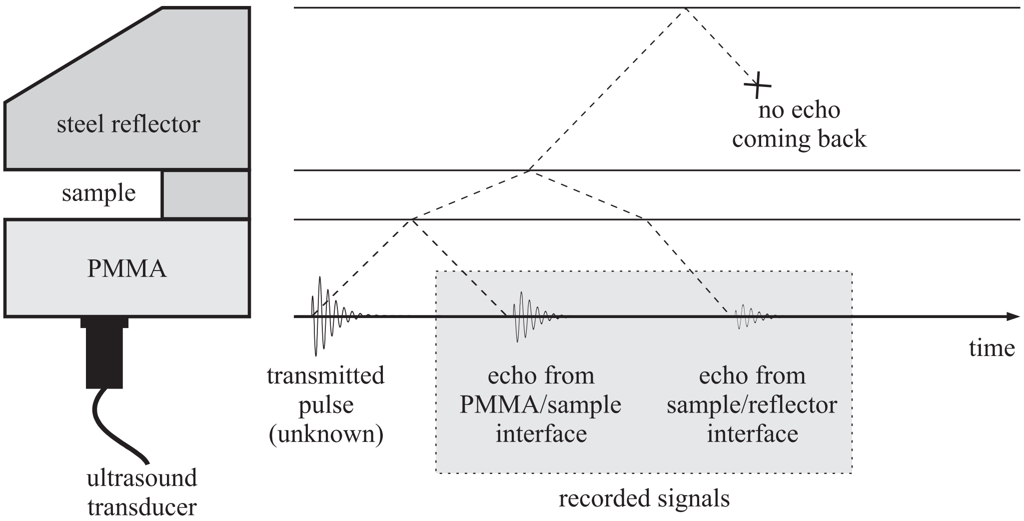

Figure 3 : Principle of the density probe. An echo is reflected at the PMMA/sample interface. A second echo from the sample/reflector is recorded. The two are used to determine specific acoustic impedance and speed of sound of the sample.

Compensation for temperature changes

Once the temperature is known, the specific acoustic impedance [1] of the buffer-rod, z_{br}, can be calculated accurately, as

$$z_{\text{br}} = \rho_{\text{br}}(\hat{T})c_{\text{br}}(\hat{T}), \tag{9}$$

where $\rho_{\text{br}}(\hat{T})$ and $c_{\text{br}}(\hat{T})$ are the density and the speed of sound of the buffer-rod, respectively, at the estimated temperature $\hat{T}$. Table 1 shows values of speed of sound, density, and acoustic attenuation for PMMA as function of temperature [7].

Table 1: Speed of sound, c, density ρ, and attenuation coefficient α of PMMA as function of temperature T.

T (°C)	20	30	40
c (m/s)	2775	2750	2720
ρ (kg/m^3)	1190	1188	1185
α (Np/m)	1.62	0.64	0.28

In addition to the change in density and speed of sound, the temperature change also causes a change in acoustic attenuation of the buffer-rod. The details of how to compensate for this can be found in [8].

Error analysis

There are three main sources of error that affect the technique described in the previous sections:

1. Experimental noise (random).
2. Sampling jitter (random).
3. Model error — lack of fit (bias).

The experimental noise depends on many different factors, and is assumed to be Normally distributed with zero mean. The sampling jitter comes from errors in the clock of the digitizing oscilloscope. This error is small, but when averaging the 100 echoes at each temperature, this jitter will distort the waveform of the pulse. It is therefore compensated for by estimating a sub-sample time-delay and then aligning the pulses according to an average delay [9]. This procedure will remove most of the jitter, and the remaining error due to this is assumed part of the experimental noise.

The largest source of error is the model error, stemming from from lack of fit of the polynomial model assumed in Eq. (4). Any adequate model should result in a model error that is independent of the observed variable, and without any systematic variations left.

We tested the residuals $T - \hat{T}$ and found that they were independent of the time delays τ_m, and that they follow a Normal distribution with zero mean and standard deviation, $\hat{\sigma} = 0.159$ °C. A 95% precision limit for the *average* model error is then

$$P = t_{N-1}(95) \cdot \hat{\sigma}/\sqrt{N}, \tag{10}$$

where $N - 1 = 11$ are the degrees of freedom, and $t_{11}(95) = 2.201$ is the corresponding 95% value of the *t*-distribution.

Using Eq. (10), we get the total 95% precision limit $P \approx \pm 0.1$ °C, at a zeroth order replication.

Experimental results

Measurements were made for every 5 °C in the range from 5 °C to 60 °C. The order of the experiments was randomized, to avoid introducing systematic variations stemming from fluctuations in the environmental conditions.

For each temperature, 100 echoes were collected from the interface between the buffer-rod and water. For each echo, the temperature of the water was measured. The arrival of each of the 100 echoes was adjusted in order to compensate for sampling jitter, using the sub-sample time-delay estimator by Grennberg and Sandell [9]. The 100 echoes were then averaged. For each temperature, T_m, the time-delay with respect to the echo measured at 5 °C was estimated. These time-delays, τ_m, are shown in Fig. 4.

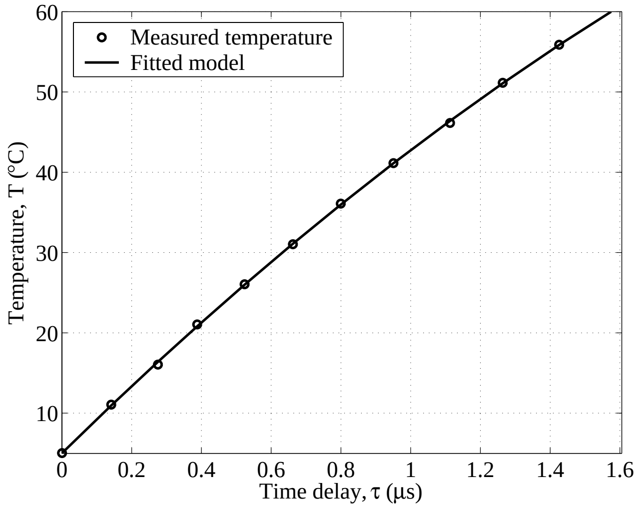

Figure 4 : Measured time delays, $\tau_m(T)$ as function of temperature changes. The solid line shows the fitted model, and the 'o' markers show the measured temperature.

The resulting polynomial model is then

$$\begin{aligned} \hat{T} &= \beta_0 + \beta_1\tau + \beta_2\tau^2 \\ &\approx 5.0252 + 42.5916\tau - 4.8710\tau^2. \end{aligned} \quad (11)$$

The model in Eq. (11) was compared to a third-order polynomial. A t-test [10] was made to evaluate if the cubic term in the polynomial contributed to explaining any systematic variation in the data. The result of the t-test showed, however, that the cubic term was not significant.

Discussion

The model presented in this paper is valid only for the actual experimental setup used in our experiments. The principle, however, is general, and a similar model using another ultrasound transducer and a different buffer-rod could easily be determined following the same experimental procedure.

Conclusions

We have presented a technique to estimate the temperature in a buffer-rod, and showed how this can be used to correct the temperature influence.

The experimental results show that the proposed second order polynomial model can be used to estimate the temperature in a PMMA buffer-rod with an accuracy of 0.1 °C at a 95% confidence level. The model is valid in the temperture range from 5 °C to 60 °C.

References

[1] L. E. Kinsler, A. R. Frey, A. B. Coppens, and J. V. Sanders, Fundamentals of Acoustics, 3rd ed. Wiley, New York, 1982.

[2] L. C. Lynnworth, Ultrasonic Measurement for Process Control: Theory, techniques, applications. Academic Press, Boston, MA, 1989.

[3] E. P. Papadakis, K. A. Fowler, and L. C. Lynnworth, "Ultrasonic Attenuation by Spectrum Analysis of Pulses in Buffer Rods: Method and Diffraction Corrections," J. Acoust. Soc. Am., vol. 53, no. 5, pp. 1336–1343, 1973.

[4] A. Püttmer, Ultrasonic Density Sensor for Liquids. PhD thesis, Otto-von-Guericke-Universität Magdeburg, 1998.

[5] J. van Deventer, Material Investigations and Simulation Tools Towards a Design Strategy for an Ultrasonic Densitometer. PhD thesis, Luleå University of Technology, 2001.

[6] J. Carlson, M. Nilsson, E. Fernández, and J. A. Planell, "An Ultrasonic Pulse-Echo Technique for Monitoring the Setting of $CaSO_4$-Based Bone Cement," Biomaterials, vol. 24, no. 1, pp. 71–77, 2003.

[7] J. van Deventer, T. Löfqvist, and J. Delsing, "PSpice modeling of ultrasonic systems," IEEE Trans. on Ultrason., Ferroelec., and Freq. Contr., vol. 47, no. 4, pp. 1014–1024, 2000.

[8] J. Carlson, M. Nilsson, E. Fernández, and J. A. Planell, "Monitoring the Setting of Injectable Calcium-Based Bone Cements Using Pulse-Echo Ultrasound," in Proc. IEEE Int. Ultrason. Symp., Munich, Germany, 8–11 October 2002, pp. 1261–1264.

[9] A. Grennberg and M. Sandell, "Estimation of Subsample Time Delay Differences in Narrowband Ultrasonic Echoes Using the Hilbert Transform Correlation," IEEE Trans. Ultrason., Ferroelec., and Freq. Contr., vol. 41, no. 5, pp. 588–595, 1994.

[10] G. E. P. Box and N. R. Draper, Empirical Model-Building and Response Surfaces. Wiley Interscience, New York, 1987.