Spatially-Resolved Determination of Transverse Wave Speed in Tissue Phantoms Using High-Frequent Ultrasound

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***Abstract*—Online temperature measurement in biological tissue would improve the hyperthermia therapy. This contribution presents a novel method for measuring the shear wave speed in biological tissue with very small echo signal amplitudes from scattering particles. Since the tissue's properties change during heating, it is not possible to average measures taken over a long time period to improve Signal-to-Noise-Ratio (SNR). The novel method relies on evaluating the signal's energy as a function of time shifted signals instead of using a cross correlation. For reproducible experiments, a tissue phantom made of polyacrylamide and algae is used.**

Keywords–Ultrasound; Shear Wave Velocity; Scattering Particles; Tissue Phantom.

I. INTRODUCTION

In cancer therapy, malicious tissue can be destructed non-invasively using hyperthermia treatment. To be sure that the destruction is complete, it is important that the whole cancer as well as a security zone reaches a temperature of at least 56 °C [1]. Due to the lack of non-invasive temperature monitoring, the used power and duration of heating is currently selected by the doctor based on his knowledge and experience. Though this method works pretty well, it is very fault-prone if there is a large blood vessel located near the tissue to be destructed. In this case, the vessel may transfer the induced heat away from the tumor, which makes it very difficult to have a good balance between complete destruction of malicious tissue and unintended impairment of surrounding tissue.

Non-invasive, locally resolved online monitoring of the tissue temperature would improve the success of the hyperthermia therapy. Since tissue has very similar acoustic properties compared to water, its longitudinal sound speed c_L is strongly dependent on temperature [2]. The locally resolved temperature measurement is introduced in [3]. However, the investigations in [4] showed that c_L does not only depend on temperature, but also on the tissue's denaturation state. Contrary, the shear wave speed c_S has low sensitivity on temperature, but is sensitive to tissue modification. To be able to measure temperature change and denaturation separately, it is necessary to know both c_L and c_S, spatially and temporally resolved.

This contribution deals with robust measurement of c_S in tissue. Section II describes the experimental setup and used materials. The experimental results are presented in Section III. Since the ultrasound signals backscattered by the tissue's structure are very small, it is indispensable to improve the SNR, which is described in Section IV. Finally, Section V provides a conclusion and an outlook of future research.

II. DESCRIPTION OF EXPERIMENTS

A. Tissue phantoms

To ensure reproducibility, instead of real biological tissue we are using tissue phantoms made of 5 % polyacrylamide gel (26.9 % acrylamide, 1.4 % bisacrylamide, 71.7 % water as well as ammonium persulfate and N,N,N',N'-tetramethylethylenediamine to start polymerization). The gel is doped with Chlorella Vulgaris, single-celled green algae that act as scatter particles. This green alga is a good choice, because it behaves like a real cell, but also is very robust and easy to grow.

B. Measurement setup

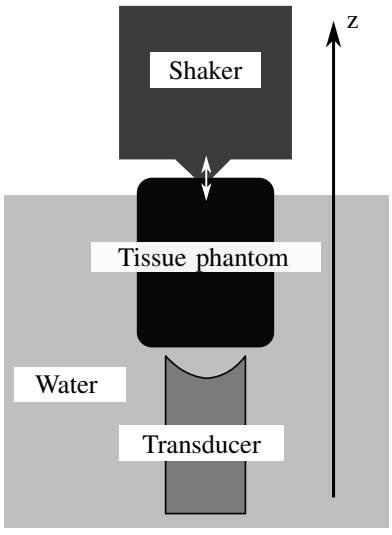

Figure 1. Setup for measuring shear wave speed c_S.

The measurement setup consists of the tissue phantom described in Section II-A, an ultrasound transducer and a shaker, which is in contact with the phantom (Figure 1). For better wave propagation, the transducer and the tissue phantom

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are stored in water. The oscillation generated by the shaker is coupled into the phantom, where a shear wave starts to propagate. This leads to a movement of scattering particles, such as algae cells, inside the phantom. Since the shear wave velocity is in the range of a few meter per second only, it is possible to observe the cells' movement using longitudinal ultrasound waves with a velocity of $c_L \approx 1500\,m/s$ and high pulse repetition rates. The shear wave speed c_S is calculated from the observed cell movement in various depths inside the phantom. The positions are selected windowing the ultrasound signal.

To investigate shear wave propagation at different temperatures and degrees of denaturation, the water may be heated by a thermostat. Due to the outgasing of the water, and thus rising air bubbles, the transducer is located beneath the phantom. This ensures that no gas bubbles accumulate in front of the transducer, which would disturb the measurement.

III. Measurement results

Using several A-scans, it is possible to observe the shear wave. Figure 2 shows a M-Mode scan of the tissue's movement. It can be clearly seen that the echoes from the tissue phantom's surface show the movement induced by the shear wave. Using the time difference of two matching oscillation states from top and bottom surface (vertical lines in Figure 2) and the sample's thickness, the shear wave speed can be calculated. In the presented experiment, this yields to a mean speed of $c_S \approx 7.8\,m/s$. This value also matches values from literature, as shown in [5].

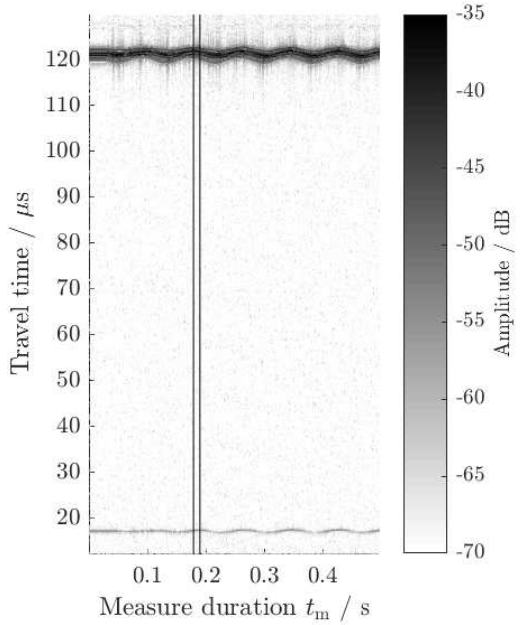

Figure 2. M-Mode image of ultrasound signals reflected by the tissue phantom.

The oscillation of the surfaces can be recovered using a correlation analysis. The maxima of the windowed signal's cross correlation give the surface's position at the arrival time of the signal. This is shown in Figure 3. Fitting a sinus to these data gives information about the current oscillation state, especially the phase.

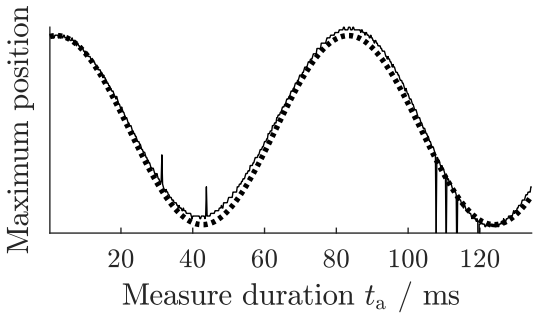

Figure 3. Positions of the cross correlation's maxima of echoes from tissue's bottom surface (solid line) and sinus fit to the data (dotted line).

Unfortunately, this method is only applicable for signals with a good SNR. As shown in Figure 2, this condition is only met on large interfaces with sufficient impedance difference. Since the cell's echo amplitude is only a little bit bigger as the noise amplitude, the cross correlation function is not able to distinguish between signal part and noise and thus provides wrong results. The SNR may be improved by increasing the number of measured cycles with at least one shear wave period and then averaging over these signals. However, the measure time would then increase, which in practice is not acceptable.

IV. Evaluation of signals with low SNR

In contrast to the cross correlation of the signals, in this section, the signal's energy as a function of time shifted signals will be evaluated. If several similar signals are superimposed, the resulting signal energy will increase while the resulting noise energy decreases. However, this will only work, if both transducer and reflector stay at a constant position over time.

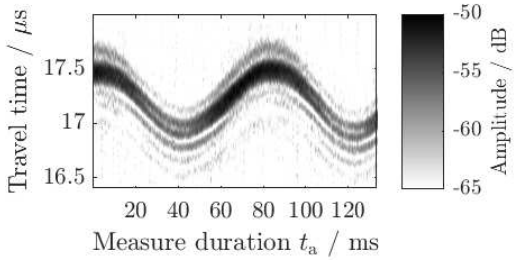

Figure 4. M-Mode picture of ultrasound signals reflected from the phantom's bottom surface.

The signals shown in Figure 4, which is a detail of Figure 2, will not sum up constructively on superimposing along measure duration, because the surface's position does change. To improve SNR as described above, the signals will need to be time-shifted with a time resulting from the shaker's oscillation y_S. The oscillation can be expressed by

$$y_S(t, \varphi) = a_S \sin(\omega_S t + \varphi) \quad (1)$$

where ω_S is the known shaker's angular frequency. The amplitude a_S depends on the phantom's damping and the travel time of the shear wave, however, it may be estimated using the

surface's echoes. The time-shift t_{sh} used to align the signals is described in (2).

$$t_{\mathrm{sh}}(t_{\mathrm{a}}, \varphi) = \frac{a_{\mathrm{S}}}{c_{\mathrm{L}}} \sin(\omega_{\mathrm{S}} t_{\mathrm{a}} + \varphi) \tag{2}$$

The time t_{a} is the arrival time of the ultrasound pulse. So, the single parameter left to determine is φ, which may be varied.

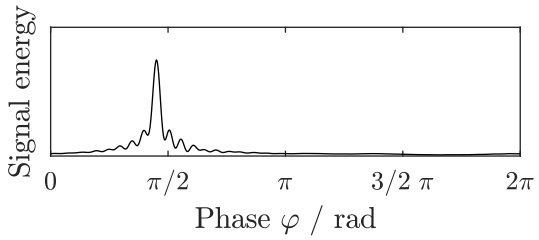

Figure 5. Signal energy as a function of phase shift φ. The maximum marks the current phase φ_{m} at time t_{a}. For this example the best phase is $\varphi_{\mathrm{m}} = 1.413\,\mathrm{rad}$

Figure 5 shows the calculated phase dependent signal energy using (2) for the signals shown in Figure 4. The maximum in the signal energy indicates the phase φ_{m}, where the model described by (1) maps the oscillation in the chosen window best.

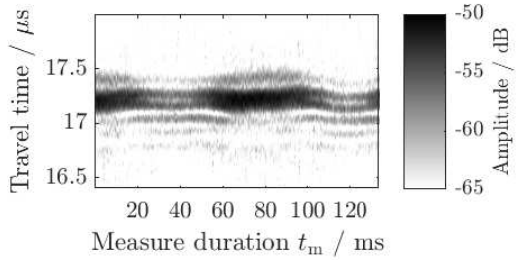

Figure 6. Time-shifted signals from Figure 4 using the phase determined with signal energy method.

The presented method can be tested by shifting the echo signals with the determined phase. This in done in Figure 6. If the model and the determined phase are correct, the figure should show all echo signals at the same travel time displaying horizontal lines. Apparently, this works pretty well in the presented example, although the form of the echo signals varies depending on oscillation state.

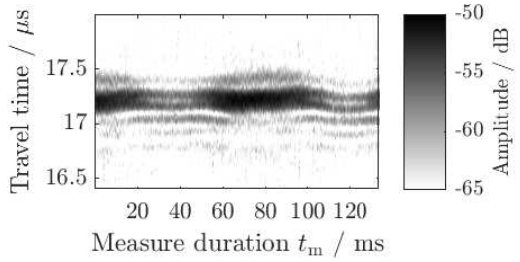

Figure 7. Time-shifted signals from Figure 4 using phase from cross correlation.

For verification, the signal shift shown in Figure 6 is also done with the phase determined by the cross correlation method introduced in Section III and is shown in Figure 7. Since the determined phases ($\varphi_{\mathrm{c}} = 1.411\,\mathrm{rad}$ and $\varphi_{\mathrm{m}} = 1.413\,\mathrm{rad}$ from cross correlation method and signal energy method, respectively) are almost equal, it is consistent that Figures 6 and 7 almost show the same pattern.

When windowing the ultrasound signals, it is possible to determine the shear wave's phase at different depths z. This allows a spatially resolved identification of the shear wave's speed $\mathrm{c_S}$ with both methods, but for a low SNR the cross correlation method is not applicable.

V. Conclusion and Outlook

The knowledge of the shear wave's speed may allow to distinguish between the effects of denaturation and temperature change on the longitudinal wave speed $\mathrm{c_L}$. This would improve the non-invasive temperature monitoring and thus enhance quality of hyperthermia therapy.

Due to its slow propagation speed in tissue, shear waves may be observed using high frequent longitudinal ultrasound waves. This contribution proposes a method to determine the shear wave's propagation speed spatially resolved in biological tissue. For better reproducibility, we use a tissue phantom made of polyacrylamide and algae. The shear waves are generated using an external shaker.

Since the shear wave causes moving reflectors, it is not possible to improve the signal quality by recording the same scene multiple times and then averaging to reduce noise. The presented novel method evaluates the energy of superimposed time-shifted signals and is capable to deal with signals that have a low SNR. A comparison with a method using the cross correlation of signals from a big interface confirmed the functionality and accuracy of the presented approach. Currently, we are improving the novel method's robustness to work with signals that have a very poor SNR, such as echoes from moving scattering particles.

Acknowledgment

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