NOVEL APPROACH FOR LEVEL MEASUREMENT IN LIQUID TANKS

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Abstract

A widespread measuring task in chemistry, food industry or biotechnology is the determination of fill levels in liquid tanks. The aim of this paper is to present a new contactless and non-invasive measuring method based on ultrasonic time-reversal and correlation techniques that is suited for both point level and continuous range measurements. Furthermore this method enables fill levels to be calculated even if the direct path from the sensor to the liquid surface is obstructed.

This article will present the principle of the measuring system as well as the procedure of simulation and signal processing considering sinus burst excitation as example. The simulations will demonstrate the excitation of a virtual sound source in the liquid. The appliance of pseudo-random bursts in comparison to this basic approach will be discussed as well as the limits of the new technique.

Introduction

The determination of fill levels in liquid tanks is still under development as the measurement techniques have to meet the increasing requirements of modern processes in chemistry, food industry or biotechnology. In some applications it is not possible to install mechanical measurement devices, e.g. floats. For this reason contactless and non-invasive techniques have been developed [1]. One common method is the ultrasonic pulse-echo measurement, but it is still limited to simple applications. If obstacles inside the tank prevent the direct view of the acoustic sensor to the liquid surface or if the liquid is inhomogeneous, the well-known time-of-flight measurement fails.

A novel solution to this problem is the use of time-reversal acoustics [2]. The undisturbed superposition of sound waves permits the generation of virtual sound sources at boundary layers even if the direct propagation is disturbed. Thus it is possible to excite a virtual ultrasonic sound source at the surface of every fill level of interest. The resulting echo-signals will correlate with the time-reversed transmitted data and a time delay should be observable depending on the actual deviation from the refocused fill level. Simulations demonstrate that it is possible to excite virtual sources and that it is possible to determine asserted fill levels. In addition, the methods reliability is analysed with appropriate pseudo-random bursts in comparison to sinus burst excitation. The achievable enhancements are based on certain conditions that are discussed at the end of this article.

Theory

In this application the time-reversal consists of two steps. At first an ultrasonic burst $\bar{x}(t) = x(T_a - t)$ is sent only once by a line array at the surface of the liquid and recorded by a transducer array at the bottom of the tank (Figure 1, 2). Subsequently the time-reversed responses are retransmitted into the liquid, where the excited wave propagates back to its origin on many different paths. The constructive superposition leads to a virtual sound source $\vec{x}(t) = x(t)$ at the liquids surface boundary and its responses $y_i(t)$ which should be similar to $\vec{y}_{\mathrm{Ref},i}(t)$ after real excitation.

In order to model the sound propagation, the tank was divided into four parts (Figures 1). Close to the surface, at the beginning of transmission there is the real or virtual transducer array followed by a homogeneous area that is modelled with a simple time delay $T = (h_2+\Delta h)/c = (h_0-h_1+2\Delta h)/c = T_0+2\Delta h/c$, depending on the positive or negative deviation Δh of the refocused fill level and the liquids sound velocity c. Afterwards there is a multiple reflecting area with the pulse responses $g_i(t)$ and eventually there is the transducer array at the bottom of the tank. Additional backscatter $b_{1/2,i}(t)$ will be disregarded in this article. With this, the cross correlation between $\vec{y}_{\mathrm{Ref},i}(t)$ and $y_i(\Delta h,t)$ can be quoted [3]:

$$\phi_{\vec{y}_{\mathrm{Ref},i}y_i}(\tau) = E\left\{\vec{y}_{\mathrm{Ref},i}(t-\tau)\cdot y_i(\Delta h,t)\right\} = \phi_{\vec{y}_{\mathrm{Ref},i}\vec{y}_{\mathrm{Ref},i}}\left(\tau - \frac{2\Delta h}{c}\right)$$

Similar to conventional time-of-flight measurements the cross correlation is the shifted autocorrelation of the reference signal $\vec{y}_{\mathrm{Ref},i}(t)$. On the one hand asserted

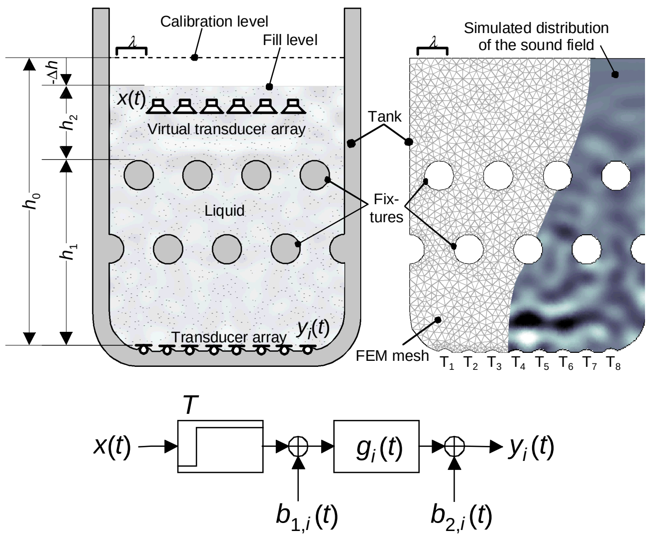

Figure 1: Tank geometry ($h < h_0$), its representation in FEMLAB© and model of sound propagation

fill levels could be identified by means of the maximum in the correlation functions. On the other hand the time delay $\tau(\phi_{max})$ is directly proportional to the deviation from the refocused level h_0.

$$h = h_1 + h_2 = h_0 + \Delta h = h_0 + \frac{\tau(\phi_{max}) \cdot c}{2}$$

The finite element simulation will confirm this conclusion and will show to what extent the influence of backscatter from the time-reversed signals is negligible, especially for pseudo-random burst excitation.

Simulation and Signal Processing

The principle of the measuring system will be discussed with the simulation tool FEMLAB©. The advantage of a computational simulation is that there is no interference from measurement equipment and the time-reversal process as well as the noisy backscatter are observable. Thereby it is possible to improve the refocussing by simply changing the experiment set-up on the computer. These advantages face the required amount of memory and numerical accuracy, which is intimately connected with computational effort.

For transient simulations FEMLAB© requires a few settings. First of all a user-defined geometry has to be drawn and a differential equation has to be defined. In order to reduce the required computing power, a two-dimensional wave equation is used.

$$\frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = \frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2}$$

The applied boundary conditions are generalised Neumann conditions. Either the boundary source term b is set to zero (reflection) or it is set to the source term $s(t)$ which simulates the excitation of a plane wave at each transducer element T_i. The boundary absorption coefficient q is always assumed to be zero.

$$n \cdot \Delta p + q \cdot p = b = \begin{cases} 0 & - \text{ boundary is reflector} \\ s(t) & - \text{ boundary is source} \end{cases}$$

In this article four different bursts with a center frequency of 25 kHz are used for excitation (Figure 2). One is a sinus burst of 2.5 wavelength (a), the other three are pseudo-random bursts of varying length (b, c, d). The signal bandwidths are nearly the same so that there is no difference in the autocorrelation peaks widthwise. The sound velocity is set to $c = 1250$ m/s (e.g. diesel), so the wavelength is $\lambda = 5$ cm. One calculation step is set to 5 µs which limits the signal bandwidth to 100 kHz. To comply with the spatial Shannon Theorem the largest mesh edge is approximately 1.2 cm leading to a reduced signal bandwidth of 52 kHz.

The initial excitation was simulated with a transmitting line array of 6 elements at the liquid surface. The first 0.5 to 0.7 ms (T_{TR}) of the burst responses that are unequal zero are recorded, time-reversed and retrans-

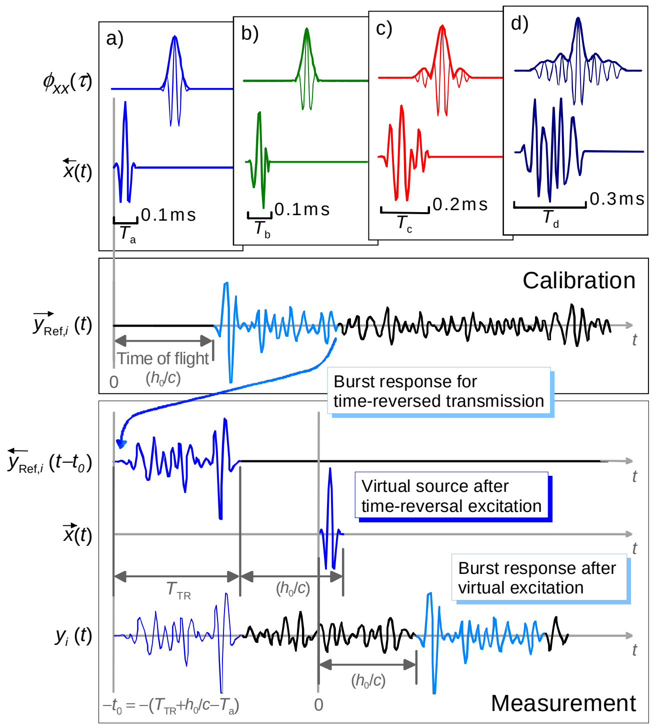

Figure 2: Applied signals and their processing

mitted into the tank. The time-reversed transmission was repeated for deviations of maximal $\pm\lambda$ in increments of $\lambda/8$. Further calculations search for correspondence between the reference signal $\vec{y}_{Ref,i}(t)$ and the echo $y_i(t)$ after a time delay $t_0 = T_{TR} + h_0/c - T_a$. The application of pseudo-random bursts should enhance the identification because there will be a longer impact of the fill level on the refocused wave train.

Results

After each simulation, the pressure amplitude distribution in the tank could be visualised. Figure 3 shows the real and virtual excitation of the applied sinus burst at three time steps. The colour indicates the amplitude of the local sound pressure (white→high pressure, grey→0, black→high negative pressure), the

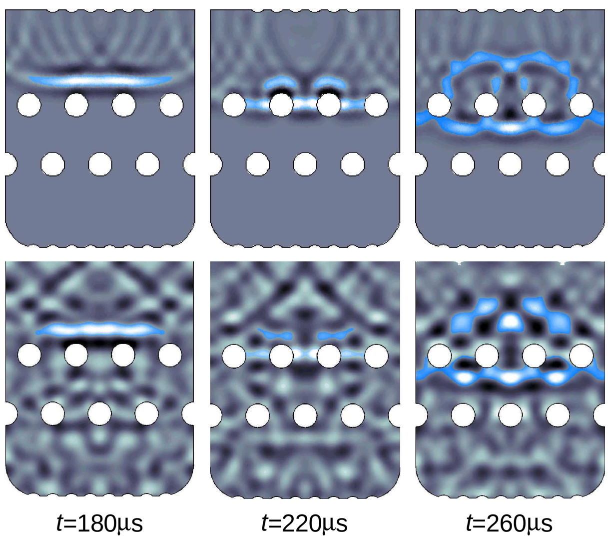

Figure 3: Burst with real and time-reversed excitation

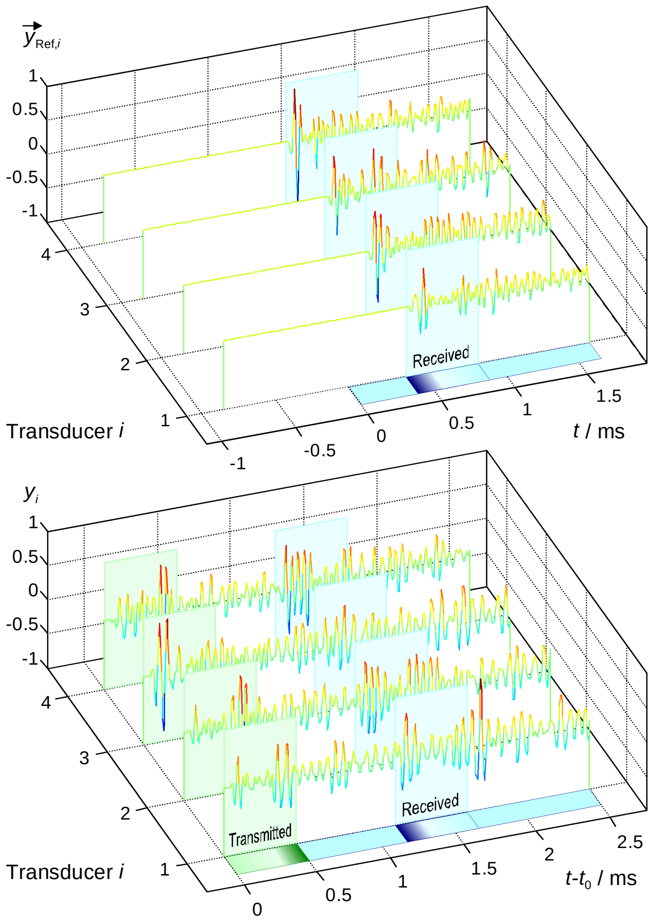

Figure 4: Sinus burst responses (a) with real (top) and time-reversed excitation (bottom)

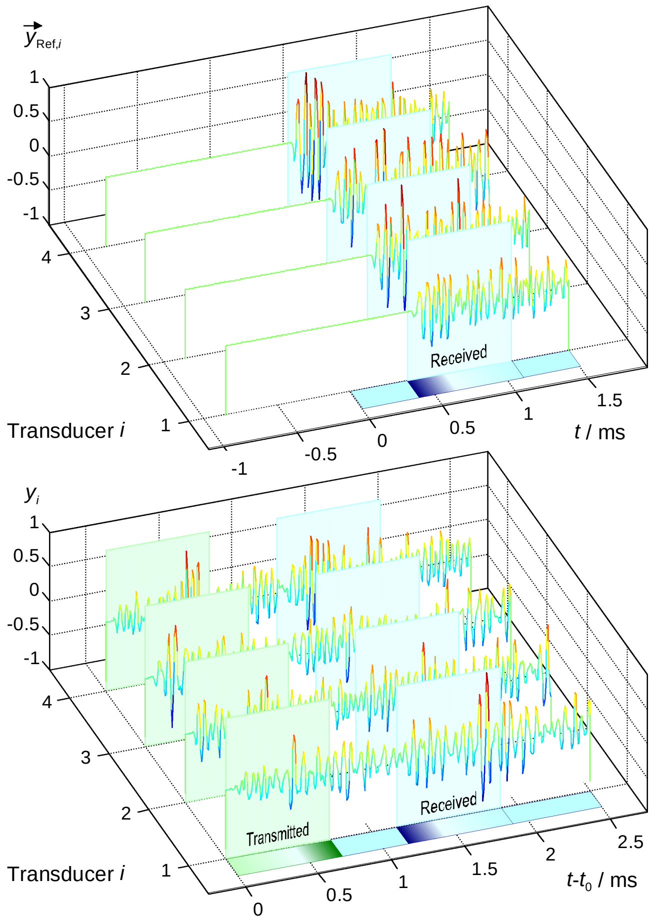

Figure 5: Pseudo-random burst responses (d) with real (top) and time-reversed excitation (bottom)

initial wave train is dyed blue. The sequence impressively shows the reconstruction and propagation of the burst at the liquid surface. Contrary to the real sound source the time-reversal excitation evokes a lot of additional backscatter which statistically depends on the transmitted sequence. This complicates the above-mentioned identification of the echo signals.

With succeeded refocussing the echo after time-reversed excitation should be similar to the non-reversed reference signal. Figure 4 and Figure 5 exemplify all burst responses for sinus burst excitation (a) and the longest pseudo-random burst (d). The echo-functions $y_i(t - t_0)$ in Figure 4 obviously show the expected similarities, wheras the echos in figure 5 do not show any similarities to $\vec{y}_{\mathrm{Ref},i}(t)$.

Nevertheless further processings point out the similarities. Therefore the 8 discrete correlations between $\vec{y}_{\mathrm{Ref},i}(t)$ and $y_i(\Delta h, t - t_0)$ are calculated and averaged. One selected correlation and its envelope are plotted in Figure 6. There are many consecutive and declining maxima indicating multiple reflections of the refocused burst between the liquid surface and the obstacles. The relevant maximum $\phi_{\max,1}$ is determined in a time slot (W1) after the preassumed time-of-flight as all signal energy before could only be backscatter information. The maximum tends to decline with positive deviations from the focused fill level while the maximum increases with negative deviations (Figure 7). Contrary to expectations the maxima disperse all the more, the longer and more complex the initial sequence is. Multiple reflections superpose the original wave train and make an identification impossible. This effect is known in presence of “gras”, i.e. particles in size of one wavelength and above [4].

In either cases the appropriate time delays τ show the predicted coherence to the deviations Δh of the reference fill level (Figure 8). The corresponding corre-

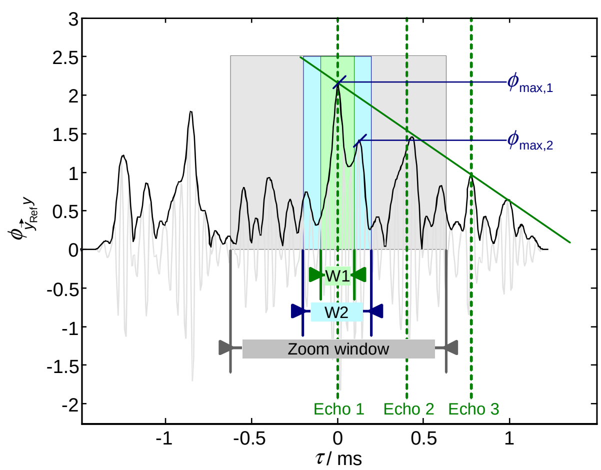

Figure 6: Selected correlation function

lation coefficients ρ are listed in Table 1. They are almost equal for the sinus burst (a) and the pseudo-random burst of the same length (b), but they decrease with increasing sequence length (c, d).

Table 1: Comparison of different bursts

	ρ	V_{min}	V_{mid}	V_{max}
a) Sinus	0.9969	1.2623	3.3492	13.9899
b) PRN_1	0.9966	1.0401	2.2610	7.7059
c) PRN_2	0.9931	1.0916	2.5181	7.9769
d) PRN_3	0.9939*	1.0627	1.6199	2.8004

*$\Delta h = -5\lambda/8$ neglected

For further evaluation of the influence of the applied bursts on the robustness of the method the time slot was enlarged (Figure 6, W2) and the proximate maximum $\phi_{max,2}$ was determined. Table 1 compares all ratios V of $\phi_{max,1}$ and $\phi_{max,2}$. The minimal ratio V_{min} is continuously decreasing from a to d, whereas the averaged and maximal ratios V_{mid} and V_{max} are maximal for sinus burst excitation and when the pseudo-random wave train is nearly as long as twice the distance to the first obstacles (c). The robustness gets worse when the wave train is longer than twice this distance (d) because ambiguities in the correlation functions arise which confirm the “gras”-hypothesis.

Conclusion

Based on FEM-simulations, the sound propagation inside a liquid tank was investigated. Thereby it could

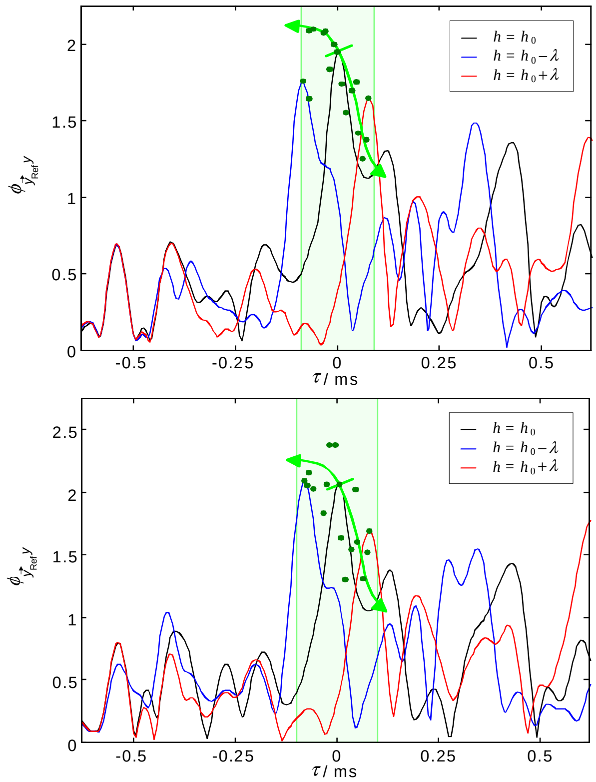

Figure 7: Zoomed correlation functions and determined maxima (dots) for sinus (top) and shortest pseudo-random burst excitation (bottom)

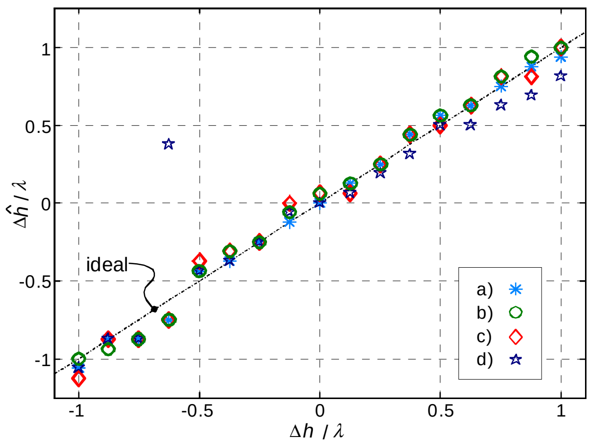

Figure 8: Preset (Δh) and calculated deviations ($\Delta\hat{h}$)

be proven that it is possible to generate a virtual sound source at every desired point of interest even if there are fixtures installed inside the tank. Based on the virtual source, a model for sound propagation has been developed and applied to fill level determination. For this reason, bursts of different length and shape but comparable bandwidth have been analysed for varying fill levels. The simulations have shown that each fill level of interest could be identified without installing new sensors in the tank. Furthermore deviations of maximal one wavelength could be determined, whereby the robustness of the method decreases in the presence of “gras” when the initial wave train is longer than twice the distance to the first obstacles. With this, the maximal sequence length must not be longer than this wave train in the liquid.

There are different possibilities to enlarge the measuring range. At first different levels could be scanned sequentially. Apart from that the algorithm could start with low to high frequencies, successively approximating the real fill level. Thus the greatest advantage of the time-reversal approach is its flexibility. The method is suited for both continuous range and point level measurement. Furthermore the time-reversal process concentrates the whole signal energy to one point or area of interest at one time. With this the influence of disturbing backscatter should be minimised.

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