APPROACH OF CONTINUOUS CHARACTERISATION OF LIQUID MULTI-COMPONENT MIXTURES

M. Gulsch[+], B. Henning[+], S. Prange[#] and J. Auge[#]
+ University of Paderborn, Electrical Measurement Techniques, Germany
# Institut f. Automation und Kommunikation (ifak), Germany
henning@emt.upb.de

Abstract

Currently there are ultrasonic sensors to measure flow, liquid level, concentrations or to monitor the process course. In several processes the investigated media is a mixture of liquid and solid ingredients. The use of ultrasonic sensor systems will become very complicated if gas bubbles appear at the measurement place caused by chemical reactions, high temperature or fast flow this means under typical process conditions. The appearance of gas bubbles falsifies the measured absorption and also the velocity. The sound propagation in liquid mixtures is influenced in a complex manner for instance by solid particles, rapid changes of temperature, and liquid droplets of other density in the measured liquid simultaneously. For the detailed investigation of the influence of bubbles on sound propagation, an experimental setup was build. This setup permits the comprehensive processing of transmitted and scattered signals. Using a smart signal processing it is possible to find a reliable indication for gas bubbles.

Introduction

Today there are many different ultrasonic sensors to measure flow, liquid level and concentrations or viscosity in several processes. One of the biggest problems by doing the measurement using ultrasonic sensors is the appearance of bubbles at the measurement place caused by chemical reactions, high temperature or fast flow. These bubbles falsify the received signal and the measurement becomes erroneous. Therefore, it is useful to know if there are gas bubbles or not. It is important to obtain the information about bubbles in real-time, however the detection of the signal amplitude is not reliable to detect gas bubbles. The amplitude is influenced by solid particles, rapid changes of temperature and liquid droplets of other densities in the measured liquid. These arguments are the motivation to find new possibilities to detect the appearance of gas bubbles in liquids independent of the transparency and the rheological properties of liquid. Commercial ultrasonic measurement systems are not able to distinguish between a falsified measurement caused by bubbles or a real change of the process situation. Today there are some systems to detect bubbles and classify them. For example the 'acoustic bubble spectrometer®' built by dynaflow [1]. This system works with long signals at different frequencies. Other systems analyse only the emitted sound of the bubbles by detecting the second harmonic of the bubble resonant frequency [2]. However the aim of this research is to find reliable indicators in the received pulse of commercial ultrasonic measurement systems to detect bubbles at the measurement place. Further investigations have shown that bubbles inside the measurement place changes the velocity in different frequency ranges depending on the bubble diameter [3][4]. This effect is called dispersion and is typical for bubble loaded liquids. But bubbles not only falsify the transmitted signals, they are also the reason for the scattering effect. This scattering effect is used for example in medical ultrasonic diagnostics. Because bubbles and solid particles in liquids are an inhomogeneity, the ultrasonic signal is scattered. The scattered signal depends on the diameter of the bubbles and particles. The following research activities deal with the new approach to characterise the transmission and the scattering effects of ultrasound in bubble loaded liquids. It will assess the usability for commercial ultrasonic pulse based measurement systems to make them more insensitive against bubbles inside the measurement place.

Experimental Setup

An experimental setup was built to investigate the transmitted and scattered signals influenced by bubbles (see Figure 1).

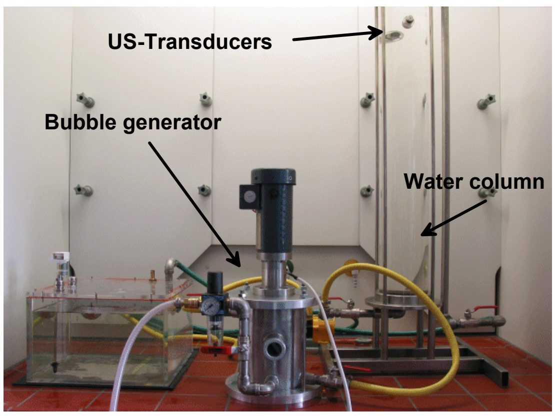

Figure 1: Experimental setup to generate bubbles with a defined diameter distribution by adjusting the flow rate and holding the temperature constant

To generate bubbles, a mechanical solution was favoured. A bubble generator was built to generate bubbles with a defined quantity and diameter distribution. Thereafter the bubbly water is pumped into a water column containing three ultrasonic transducers. The geometrical adjustment, shown in Figure 2, is chosen to receive a transmitted and a scattered signal. One transducer is used as transmitter and the other two transducers are used as receiver. All transducers have a resonating frequency of 1 MHz and a 3 dB bandwidth of 1 MHz. Figure 3 and Figure 4 show the sound propagation paths in the case with and without bubbles.

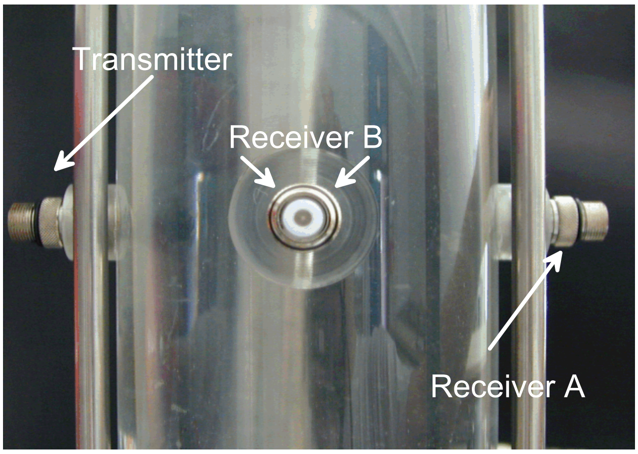

Figure 2: The transducer arrangement at the water column

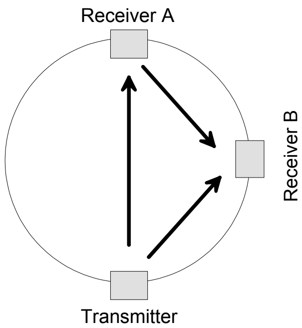

Figure 3: Signal paths without bubbles inside the measurement place

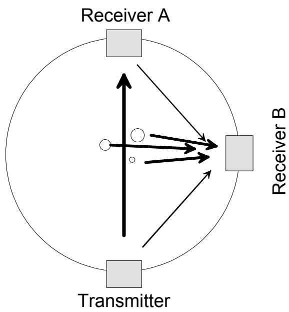

Figure 4: Signal paths with bubbles inside the measurement place

The used transmitter signal is a 1 MHz pulse (see Figure 5). The receiver signals are recorded by an analog to digital converter (25 MSample/s with a resolution of 12 bit).

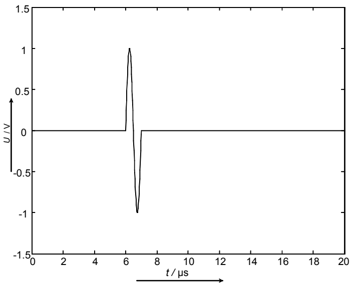

Figure 5: The transmitter signal: 1 MHz pulse

Measurement data processing

There are some mathematical ways to analyse signals in time or frequency domain. The disadvantage of the Fourier transformation and Laplace transformation is the limited time resolution if the frequency resolution is high. Also the frequency resolution reduces if the time resolution is high.

The idea is to characterise the dispersion of the pulse signal passing the water column. The Wavelet transformation is the most suitable method to analyse signals in time and frequency domain, because the Wavelet transformation makes time, frequency and amplitude visible in only one diagram [5]. Using an adapted Wavelet to the receiver signal shape it is possible to show the effect of dispersion clearly. Different Wavelets were tested, but the best results were reached with the Morlet Wavelet shown in Figure 6.

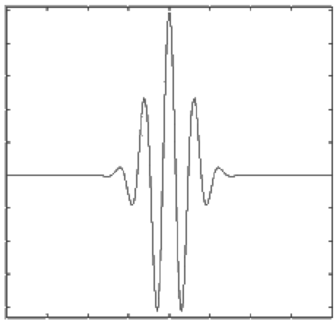

Figure 6: Morlet Wavelet

Figure 7 shows the Wavelet transformed transmitter signal. To make the signal components with very low intensity visible, the Wavelet transformation is normalised for each frequency. Because of this fact it is possible to see the pulse as a line in the Wavelet transformation. The general equation between the bubble resonant frequency and the bubble radius, originally developed by Minnaert [6] is:

$$\rho\omega_r^2 R_r^2 = 3\gamma\left(P_0 + \frac{2\sigma}{R_r}\right) - \frac{2\sigma}{R_r}$$

Where, γ = ratio of specific heat of gas (γ = 1.4 for air at atmospheric pressure),
$\omega_r = 2\pi f_r$ = resonance frequency,
ρ = density of the liquid,
R_r = radius at resonance,
P_0 = ambient pressure in the liquid (one atmosphere),
σ = surface tension.

From this equation by substituting the physical constants for air and water, the following simplification is possible:

$$f_r R_r \approx 3.28$$

The following explanations will consider the frequency range from 0.2 MHz to 1 MHz, because inside this frequency range the scattering and dispersion effect caused by bubbles of a radius from 3 µm to 16 µm is visible. The bubble radius of the generated bubbles is verified by photographs.

Experimental Results

The test signals were transmitted through the water column in different cases, without bubbles and with bubbles of different diameters. In this example and the following the 1 MHz pulse is used as a transmitter signal. The transmitted and received Wavelet transformed signals in the case without bubbles are shown in Figure 7 to Figure 9.

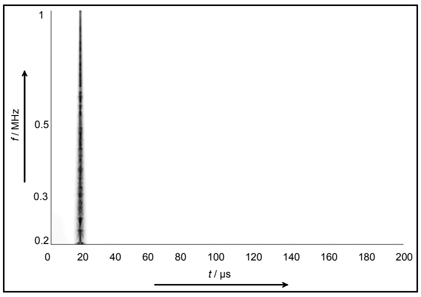

Figure 7: Transmitted 1 MHz pulse

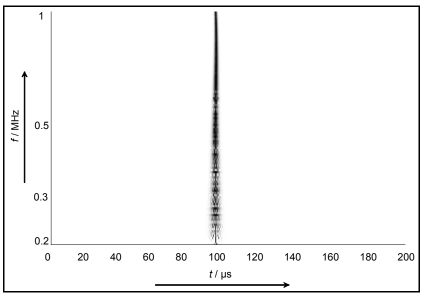

Figure 8: Received 1 MHz pulse without bubbles (receiver A)

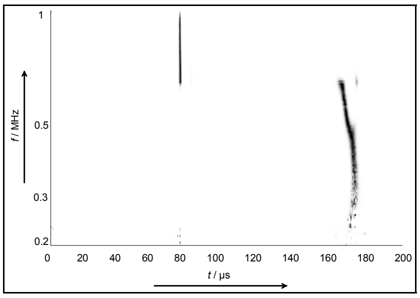

Figure 9: Received 1 MHz pulse without bubbles (receiver B)

The transmitted signal is sent 20 µs after starting the recording (Figure 7). 80 µs later, the pulse is being transmitted through the column and received by receiver A (Figure 8). This receiver signal shows no kind of dispersion.
It attracts attention that the running time to the receiver B is a little bit shorter (60 µs) than the half of the direct transmission. This comes because of the direct received sound components (Figure 3). In Figure 9, the effect of normalisation, described in Measurement data processing, is visible. The main intensity of the first received pulse, recorded with receiver B, is inside the frequency range of 1 MHz to 0.7 MHz. But there are always signal frequencies lower than 0.7 MHz at this time. They are not displayed, because the main intensity of the signal reaches the scattering receiver after being reflected at the other side of the water column with higher amplitude, in this case 150 µs after sending the transmitter pulse (Figure 3).

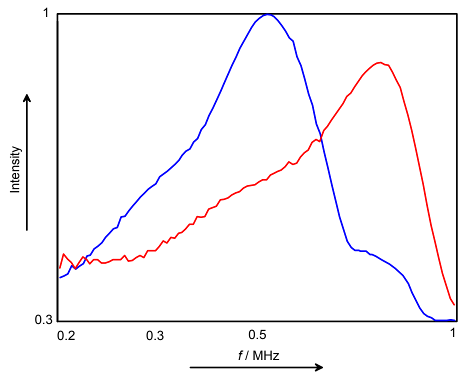

Figure 10: Intensity lines at 80 µs (red) and 175 µs (blue) in the case without bubbles, received with receiver B (Figure 9)

The frequency dependent signal intensity of the Wavelet transformed receiver signal of Figure 9 at 80 µs and 175 µs is shown in Figure 10. This figure helps to understand, why the lower frequencies in the first received pulse and the higher frequencies in the second received pulse in Figure 9 are not visible. The red intensity line corresponds to the first pulse and the blue line to the second. It is easy to see that there are lower frequencies in the first received signal, but they have a lower intensity than the lower frequencies in the second received signal. That is the reason why they are out of scale in the first received pulse. The crossing point of both lines is near 0.7 MHz, this corresponds to Figure 9. The received signals are filtered with a bandpass filter with cut off frequencies of 0.2 MHz and 1 MHz. That is the reason why the intensity line is going down near 1 MHz. In the case of bubbles inside the measurement place, the scattering receiver gets the main signal intensity from the scattered objects and not on the direct path (Figure 4). The generated bubbles have an average radius of 3 µm to 16 µm, this corresponds to the bubble resonant frequency of 1 MHz to 0.2 MHz. Because of the normalisation of each frequency the direct path is not longer visible in the Wavelet transformation but also existent. In this configuration receiver B gets the main signal intensity in this way, shown in Figure 4. The corresponding Wavelet transformed receiver signal is shown in Figure 11. It is visible that the delay time of the frequencies from 1 MHz down to 0.2 MHz is 80 µs in reference to the pulse in Figure 9. This is 20 µs longer than in the case without bubbles, because the main propagation path is now displayed like in Figure 4. This path is nearly as long as the direct transmission path.

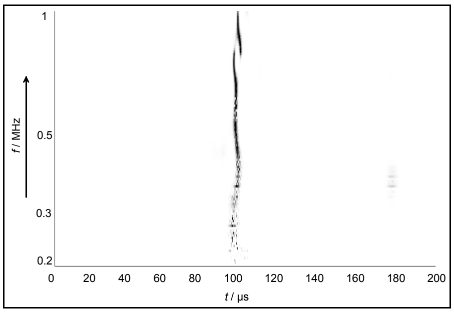

Figure 11: Wavelet transformed received signal at receiver B with many bubbles

Conclusion

The presented results show that it is possible to detect bubbles inside the measurement place with ultrasonic measurement devices, by using the Wavelet transformation to detect scattering and dispersion effects caused by bubbles. Both effects correspond to each other and can be used for bubble detection in commercial measurement systems. By using both signals, the transmitted and the scattered, a measurement system is able to detect bubbles inside the measurement place and to distinguish between the influence caused by bubbles and caused by the change of the process situation. The next step is to look if it is possible to characterise solid particles in the same way and to distinguish between solid particles and gas bubbles. Another application is the measurement of gas volume within the liquid medium.

The combination of the shown methods and the methods described in [7] makes it possible to create ultrasonic pulse driven measurement devices which could observe processes also in bubble loaded liquids. The pulse driven ultrasonic measurement devices get a larger field of applications only by using a mathematical method to analyse different pulse signals in time and frequency domain.

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