APPLICATION OF THE ULTRASONIC TECHNIQUE FOR MONITORING WATER-SOLID FLOWS

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ABSTRACT

This paper presents an analysis of experimental data obtained from one apparatus developed to monitor two-fase flow (water-solid) on the upward direction. The flow structure was investigated using an ultrasonic apparatus consisting of one emitter transducer and three receivers at different positions along the pipe circumference. The direct transmission receiver (θ = 180º) measures the energy transmitted through the suspension flow. The side sensors (θ = 45º and 135º) measure most of the energy that comes from the scattering of the acoustic beam. The ultrasonic sensors used were of the Panametrics videoscan type, 2.25 MHz, 13 mm diameter, and longitudinal waves. The data acquisition used was the PXIe-1062Q (National Instruments), and the emitter transducer was excited at 2 kHz; the sampling period was set to 5.0 sec and the sample frequency 20 MHz. The desired multiphase suspension is made to run through the Plexiglas pipe. The circuit was designed to operate in batch, and after running through the Plexiglas pipe the flow is directed to separation tanks.. Data were obtained from 0 to 3% mass concentration of glass beads in water in an interval of 0.25%.. The ultrasonic sound wave intensity and energy were calculated using a computational procedure developed in Mat Lab™. Finally, the paper shows that the signals are fast attenuated even for very small particle concentrations, and the signals duration remains almost unchanged.

***Keywords**: Ultrasonic technique, liquid-solid flow, solid fraction, acoustic attenuation, transit time*

1. INTRODUCTION

The multiphase flow metering and the accurate monitoring of oil production impose numerous technological challenges. In the oil industry, the multiphase flow may be found in hostile environments, with aggressive fluids, sometimes carrying suspended particles. Therefore, there is an immense interest in the use of the noninvasive and real-time techniques for the disperse phase monitoring in the multiphase flow. Moreover, information about the flow pattern can benefit the fluid classification and improve the transportation processes.

The ultrasonic technique has been studied for these applications (Bernerdee 1981, Chang 1981, Carvalho 2009, Lampreia 2005, Zheng and Zhang 2004). This technique is already well established in other fields of application, such as medicine and flaw detection in solid materials. The transducers are readily available commercially at relatively low cost, and these techniques are also compact and robust.

So, this paper shows an experimental apparatus projected for the measurement of the void and particle suspension fractions by utilizing the ultrasonic technique, where the direction of the flow is upwards and the particle concentrations vary from 0 to 3% wt. The main goal of this work is to investigate the transit time, energy ratio, and acoustic attenuation measured by the transducers coupled in a solid-water flow.

Kytömaa (1995) presented a discussion about the mechanisms of acoustic attenuation in solid and liquid suspensions, where he indentified three different regimes of compression wave propagation as a function of the length scales of process. Two principal parameters are used to determine which regime a particular situation fits in. The multi-scattering regime (regime of short wavelength) for $ka>>1$, where

$$k = \frac{2\pi}{\lambda} = \frac{2\pi f}{c} \tag{1}$$

λ is the wave length, f the wave frequency, c the wave velocity in the continues phase and a the particle radius. In this situation ($ka>>1$), the particle diameters are much bigger than the wavelength, and the acoustic wave scatters uniformly in all directions, resulting in a poor penetration. For the other regimes, $ka<<1$, the acoustic wave scattering and attenuation depend on the *Reynolds* number.

In his work, Urick (1947) showed that the particles were infinitely small compared to the wavelength of the sound (long wavelength limit), and neglected the effects of scattering. In the suspension, the ratio of sound velocity as a function of solid volume behaves as a parabolic function, and consequently has a maximum or a minimum at some particular concentration. Data obtained from suspensions of kaolin (chemical composition $Al_2Si_2O_5(OH)_4$) in distilled water showed a minimum in the sound velocity (increase in transit time) for 20% v/v of kaolin. In all these experiments conducted by Urick (1947), particle size was much smaller than the wavelength, thus corroborating the assumption of long wavelength limit.

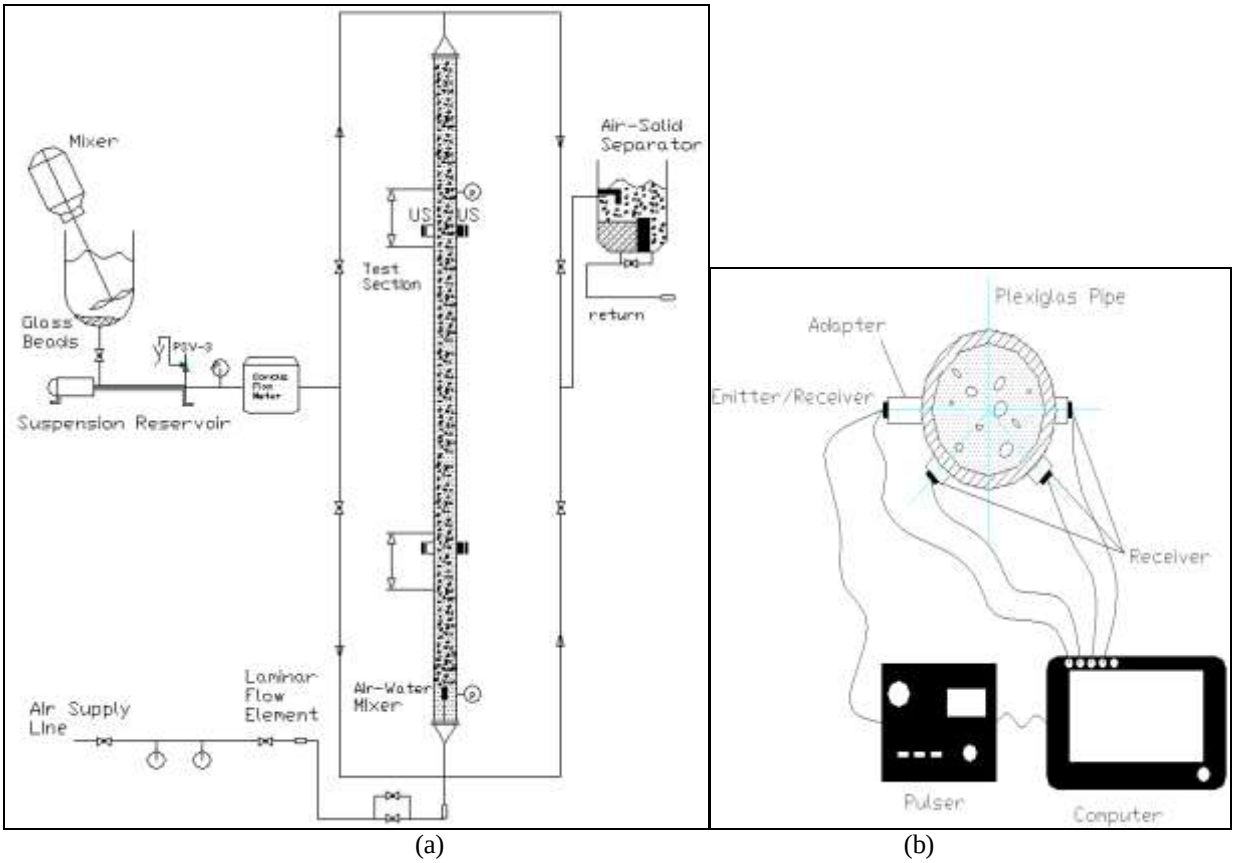
Other authors (Soong *et al*. 1995) proposed other acoustic attenuation measurement in a three-phase reactor consisting of water, glass beads, and nitrogen bubbles. They used glass beads with 80 ± 5 μm, ultrasonic pulses frequency of 2,5 MHz and the concentration was varied from 1% to 35% for a given void fraction of nitrogen. With these data the authors were able to observe a decrease in the wave transit time with an increase of the glass beads concentration. The transit time was defined as the time interval corresponding to the first distinct zero crossing of the acoustic wave at the receiver transducer. The nitrogen flow rate did not cause any effect on the transit time so defined. It was argued that the portion of the acoustic beam that is transmitted through the solid particles is speeded up by the higher sound velocity in the new medium, which explains the decrease in the transit time.

Similar to this present work, Stolojanu and Prakash (1997) performed acoustic measurements in two-phase and three-phase systems. In their work, transducers with 4 MHz nominal frequency were used. The solid loadings were up to 90% wt and the gas holdup up around 40% vol. Glass beads of 35 μm in diameter were used as the solid phase while tap water and compressed air constituted the liquid and gas phases, respectively. In two-phase systems, the transit time was observed to decrease monotonically with increasing solids concentration, the corresponding plot exhibiting a linear relationship throughout the entire concentration range tested. The measured transit times, however, were quite different from the values predicted by the phenomenological approach proposed by Urick (1947). Regarding the amplitude ratio, an exponential decay was observed with increasing solids concentration.

Zheng (2003) also presented ultrasonic data for two-phase and three-phase systems. The liquid, gas, and solid phases consisted respectively of water, air, and 500 μm glass beads; acoustic parameters were normalized with reference to single-phase liquid water. In liquid-particles flows, the standard deviations of the transit time were observed to increase with increasing solids concentration at the same time the standard deviations of the normalized amplitude were observed to decrease. Moreover, the standard deviations in liquid-solid flows were substantially smaller than those in liquid-gas flows, especially for the normalized amplitude.

2. MATERIALS AND METHODS

The experimental apparatus were assembly at the Federal University of Itajubá (LRF-UNIFEI), which allowed the measurement of multiphase flow (glass beads-water-air) in both ascendant and descendant directions. The test rig used for ultrasonic measurements consisted of one water tank followed by a pump controlled by a frequency inverter to give the desired flow rate, as shown in Figure 1.



(a) (b)

Figure 1. Schematic view of (a) water-sand-air flow test rig, and (b) ultrasonic instrumentation.

The glass beads-water mixer consists of a water-filled tank where the lower end of a 54-mm inner diameter acrylic pipe is connected. There is an electrical motor coupled to helices which mix the glass beads in the water. Inside this pipe there is a cylindrical porous media through which compressed air is injected into the water flow. The ultrasonic test section is actually a 100 mm long segment of the same 54-mm diameter acrylic pipe on to which the ultrasonic probes are attached. A 6 m long segment of acrylic pipe discharges the air-water-sand flow into a phase separator. The air is eliminated into the atmosphere while the gravity separates the sand/water, and finally the water flows back to the liquid reservoir. The test rig operating conditions, such as pressure, flow rates, and temperature, were acquired by a National Instruments CompactDAQ acquisition module, and the LabVIEW Signal Express software. The ultrasonic data were acquired separately using a National Instruments PXIe data acquisition system equipped with LabVIEW 8.6 software.

Figure 1 (b) shows the ultrasonic apparatus utilized for the measurement. An ultrasonic pulser (100 Hz - 5 kHz) emitted the signal to the emitter transducer, the ultrasonic signal was acquired by the 4 transducer receivers positioned 5 meters above the sand-water inlet, and finally the computer acquired the signal. The main reasoning behind the transducers arrangement as Figure 1b was that there should be one ultrasonic sensor in each quadrant of the pipe circumference. However, given that the bubbly flow is radial and symmetrical, from a statistical point of view, only half the circumference was instrumented. The direct transmission receiver ($\theta = 180º$) was expected to get the transit time and the energy transmitted through the sand/water flow, and the side sensors ($\theta = 45º$ and $135º$) were expected to receive at least part of the energy scattered off the acoustic beam. It is expected that a cross-analysis of the signals from all receiver transducers will disclose features of the instantaneous bubbly flow topology as well as the main aspects of the phase distribution over the pipe cross-section. The ultrasonic sensors used were Panametrics Videoscan 2.25 MHz, 13 mm diameter ultrasonic transducers.

The circuit was designed to operate in batches and after running through the Plexiglas pipe the flow was directed to separation tanks. The size distribution of the glass beads used is shown in Table 1. The concentration of glass beads varied from zero to 3% by weight in gradual variations of 0.25%. The desired concentrations were prepared in the suspension reservoir. The glass beads were weighed (±0.001 kg) and the water mass in the tank was previously measured with the Coriolis flow meter (±0.15%). The resulting uncertainty in the concentration values was estimated to be about ±0.2%. However, in running the experiments a tendency for the glass beads to settle in some singularities in the test rig was observed, which could have caused the concentration in the ultrasonic test section to vary with respect to that in the suspension reservoir. The pulse generator was excited at 2 kHz, and acoustic samples were acquired over 5 sec, which makes for 10,000 pulses in each sample. For each solid concentration, six acoustic samples were obtained.

3. RESULTS AND DISCUSSION

For this work, the review concerning the *ka* and *Re* parameters found are described as follows.

Table 1. Test condition for the ultrasonic data acquired in solid-liquid flow.

Ranges	**1**	**2**	**3**	**4**	**5**
Particles size [μm]	590 – 595	425 – 590	212 - 425	150 – 212	<150
wt [%]	0.6	54.3	38.2	6.0	0.9
ka	2.82 – 2.84	2.03 – 2.82	1.01 – 2.03	0.72 – 1.01	<0.72
δ [μm]	0.37	0.37	0.37	0.37	0.37
Re	799 – 806	576 – 799	287 - 576	203 – 287	<203

For firsts range (1, 2 and 3) of Table 1, $ka > 1$ and $Re >> 1$, and the attenuation mechanism looks like a combination of multiple scattering and inertial losses (in-phase component of the Basset force). Since the value of *ka* is not larger than the unit, the multiple scattering process is not expected to be very intense. However, the other two range, (4 and 5), the acoustic attenuation is expected to be more related to inertial effects, and it do not cause too much scattering. The following table (Tab. 2) shows the main flow conditions of this works, and also it is compared with some works found in the references.

Table 2. Comparison of acoustic data in liquid-solid systems from several authors in the literature.

Author (s)	**Present work**	**Kytömaa (1995)**	**Shukla and Prakash (2006)**	**Soong et al (1995)**	**Stolojanu and Prakash (1997)**	**Urick (1947)**
Liquid-solid system	glass beads in water	glass beads in water	glass beads in water	glass beads in water	glass beads in water	kaolin in water
Concentration range [wt.%]	0.0 – 3.0	0.0 – 60.0	0.0 – 40.0	0.0 – 35.0	0.0 – 100.0	0.0 – 63.4
Particles radius (μm)	75.0 – 300.0	12.0	0.17 – 0.55	40.0	17.5	0.2 – 2.5
ka	0.72 – 2.84	0.023	0.23 – 0.75	0.42	0.30	0.0009 –0.011
δ [μm]	0.37	0.83	0.31	0.35	0.26	0.55
Re	203 – 806	14.6	55.0 – 178.0	114.0	63.3	0.36 – 4.52
Acoustic dissipation regime	Inertial	Inertial	Inertial	Inertial	Inertial	Viscous
Trends in initial transit time with increasing wt.%	Parabolic	Exponential decrease	Exponential decrease	Linear decrease	Linear decrease	Parabolic

Table 2 shows that all the authors utilized higher solid fraction than our work (0 – 3% w/w). Related to the acoustic energy measured by the 180° transducer, very small quantity of solids already can reduce the energy which reaches to this sensor, as we can see at the Fig. 2.

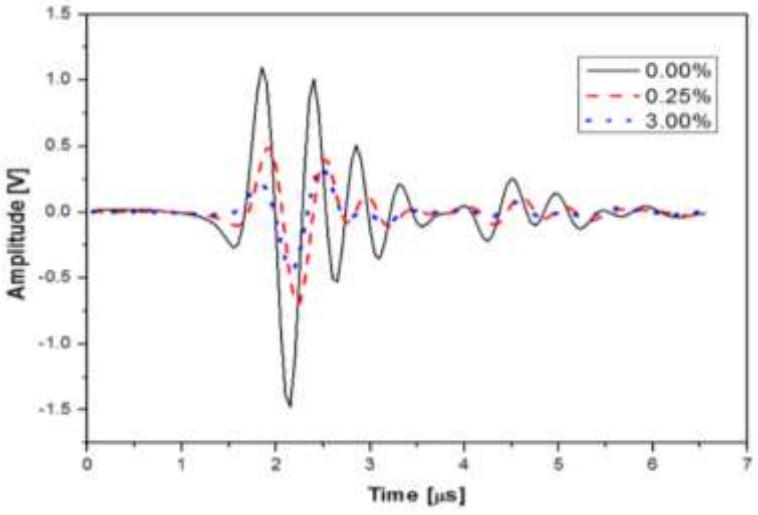


Figure 2 - Average response signals for the 180° receiver.

Figure 2 shows a representation of the average response signals for the 180° receiver, for three solids concentration: 0% (the reference), 0.25% w/w and 3.00% w/w. One can see that signals amplitudes are attenuated even for very small concentration. However, the signals duration practically maintained the same (see figure 4 ahead). Still related to the acoustic energy, Fig. 3 exhibits the average energy ratio as a function of solids concentration for 0° and 180° receivers.

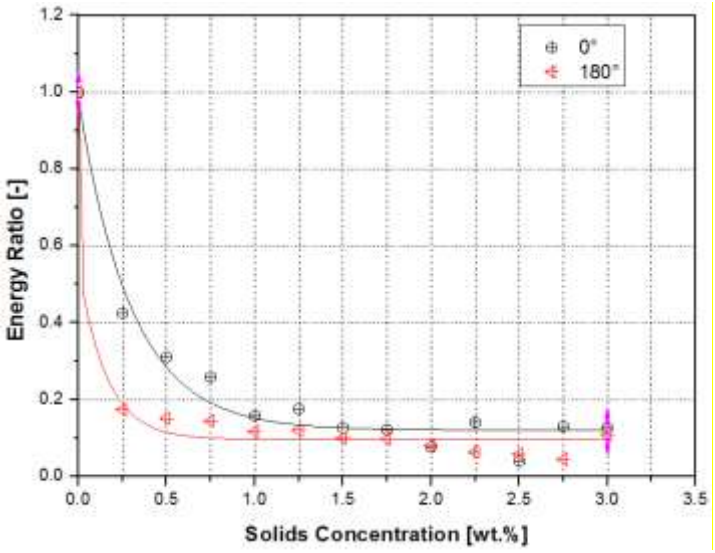


Figure 3. Average energy ratios as a function of solids concentration measured for 0° and 180° receivers.

The energy ratio measured by the 0° and 180° sensors decreased exponentially with the increase of solid concentration, and the correlation coefficients were approximately 0.97 and 0.98 (Fig 3). It is noteworthy that even for concentrations as low as 0.25% the energy ratio was already less than 0.5 and decreased to much lower values within the narrow concentration range tested. A similar behavior was observed by Soong *et al.* (1995), where 40 μm radius particles in water also corresponded to the inertial regime. On the other hand the 45° and 135° sensors did not measure any significant energy throughout the entire solid concentration. This behavior confirms the expectations that multiple scattering should not be very intense for the particle sizes in this experiment. Figure 4 shows the initial transit time as a function of solid concentration.

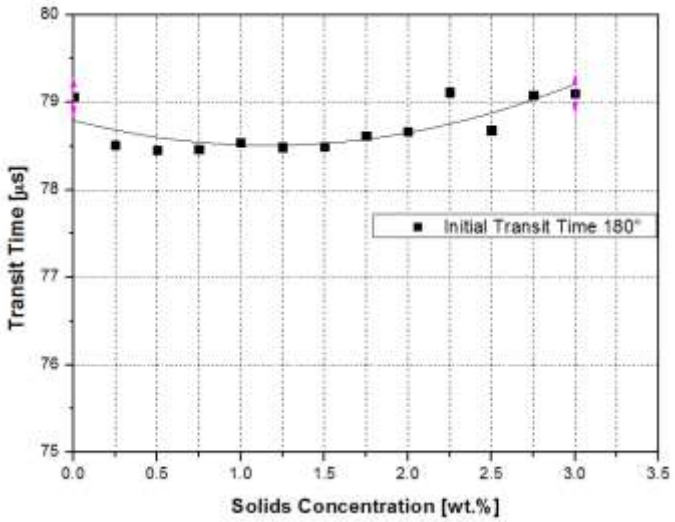


Figure 4. Transit time as a function of the particles concentration for the 180° transducer.

In Figure 4, a minimum point is observed at approximately 1.5% wt. The uncertainties in the averages were calculated from the standard deviation in 10,000 pulses of each sample, and six samples for each concentration. Nevertheless, the parabolic trend in the averages was compared with the trends in other data found in the references (Urick, 1947). But it should be said, though, that these authors did not report averages uncertainty in their data. The parabolic trend with a minimum point observed here does not agree with the others authors. For a higher solid concentration (>10 % v/v), it was observed only a decrease in the initial transit time. However, in the present investigation, for most particles $ka = 2.84$ whereas for other authors $ka < 1$. The present trends are also opposite to those verified by Urick (1947) for the viscous dissipation regime and $ka << 1$. Kytömaa (1995) points out that sound speed and attenuation each one contain complementary information and measurements that can make use of both are likely to be more robust. Nevertheless, in view of the apparent strong dependence of the transit time variation on the particle size

distribution relative to the wavelength, the use of the initial transit time to measure solids concentration would be very much dependent upon calibration for the particle sizes expected in the real application. In case this distribution could not be known beforehand, the transit time would not yield reliable information. Values below that for single-phase water would mean the entrance of energy is being speeded up by the dispersed phase. It should be kept in mind that the chronological duration of the acoustic pulse remained essentially unchanged despite the severe attenuation by the dispersed phase.

4. CONCLUSION

As a conclusion, the selection of a good ultrasonic instrumentation (transducers frequency) for measurement of solids concentration depends on the particle size distribution, the continuous phase, the concentration range desired, and the resolution required.

The initial transit time variation with solid concentration seems to be very much dependent on the particle size relative to the wavelength and, thus, prior knowledge of size distribution is a requirement for reliable measurements.

Finally, poor ultrasonic penetration due to intense multiple scattering would cause the sound beam as received by the opposite sensor to be fast attenuated. In these cases, the side sensors could provide useful information that, together with the 0° and 180° sensors, would make the measurement, as a whole, more robust.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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