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EXPERIMENTAL INVESTIGATION OF ULTRASONIC FIELD IN TWO-PHASE BUBBLY-FLOW USING RIGID STEEL SPHERE

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Abstract. *Ultrasonic techniques are low cost and non-intrusive techniques for two-phase flow measurements, especially for applications in nuclear power plants, petrochemical plants and industrial plants. Ultrasonic transducers of different frequencies and sizes generate different ultrasonic fields in different tube diameters. It is not clear how air bubbles influence the ultrasonic signal in different ultrasonic fields. The objective of this work is to investigate experimentally the attenuation of the ultrasonic signal by a steel sphere immersed in water that simulates an air bubble. The experiment was carried out in a vertical tube of stainless steel AISI 316, and of 52.8 mm inside diameter and 2.1 mm thickness. The steel sphere was of 3/16" diameter. The ultrasonic pulse-echo technique was applied for the measurement of the attenuation of the ultrasonic waves reflected from the opposite internal wall of the tube, using an ultrasonic transducer of 5 MHz. The experimental results show the importance of the transducer diameter and frequency to detect discontinuity immersed in water and the influence of tube thickness. This investigation contributes t to the analysis of the perception of the discontinuities immersed in water close to the transducer when applying the ultrasonic pulse – echo technique.*

Keywords*: bubbly flow, ultrasonic technique, pulse-echo, ultrasonic field, solid sphere*

1. INTRODUCTION

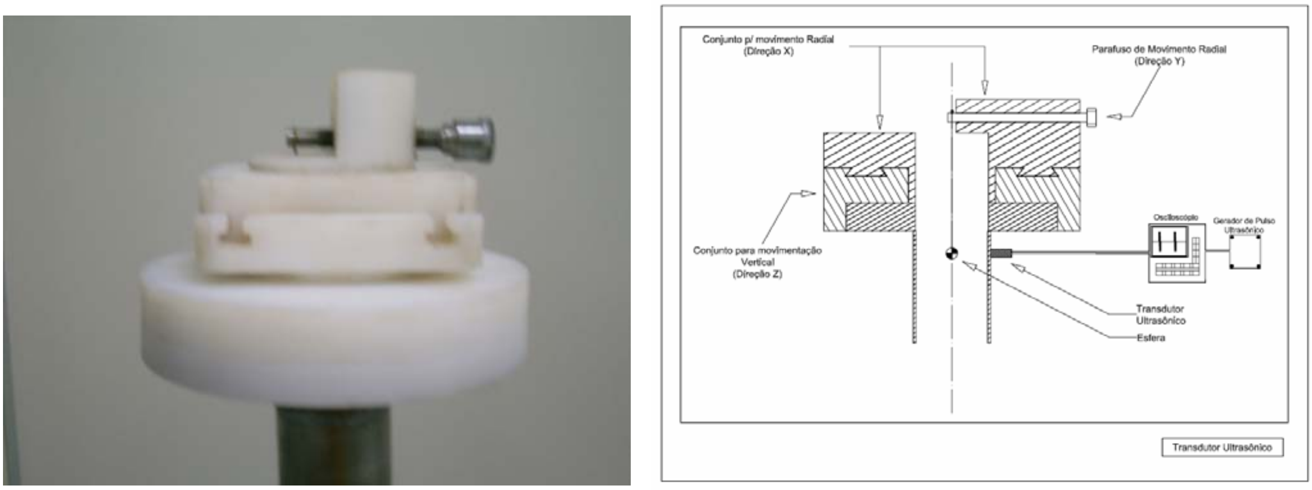
Nucleate boiling is important for the improvement of the efficiency of heat exchangers. However, it is undesirable in some cases due to the consideration of plant safety. Nucleate boiling detection is thus essential to a quick control and better efficiency in heat exchange process. Currently, there are instruments to detect bubbles in the liquid phase, as well as to measure the void fraction in heat exchangers. Due to its importance, it is always desirable to develop a new non-invasive technique like ultrasonic technique. Studies have been conducted for ultrasonic techniques in bubbly gas-liquid two-phase flow in vertical and horizontal pipes for the measurement of flow parameters like void fraction and interfacial areas. Stravs and Stockar (1985) conducted studies of an ultrasonic technique to obtain size distribution of spheres dispersed in a continuous phase but have not studied the sensitivity of transducers in relation the spheres or air bubbles. Chang and Morala (1990) developed a transmission ultrasonic technique to vertical column and a pulse-echo ultrasonic technique to horizontal tube to measurement void fraction and interfacial area in a bubbly gas-liquid two-phase flow. The two previous works did not comment about air bubble perception by transducers. In literature there are studies about interaction of reflective objects in ultrasonic fields. Anderson (1950) developed studies about sound scattering from a fluid spheres and Hasegawa et al (1992) developed a theoretical study of acoustic scattering by a rigid sphere, but they do not consider the effects of thick metal wall that holds the liquid.

The objective of this work is to study the interaction of ultrasonic field with a steel sphere and to analyze the importance of transducer frequency. This paper is organized as follows. In Section 2, the experimental setup and ultrasonic system are presented. The experimental results are presented in Section 3.The main conclusions of the work are presented in Section 4.

2. EXPERIMENTAL SETUP AND ULTRASONIC TECNIQUE

The experimental facility is composed of a stainless steel AISI 316 tube of 52.8 mm inner diameter and 2.1 mm thickness, and a device for positioning of the sphere. The device for positioning of the sphere consists of four parts: first one, the base to couple on the flange of the tube; second one, coupled in the base by means of thread and with a flat face divided in 16 parts that allows vertical displacement of the sphere with 0.125 mm accuracy, the third one is coupled in the second one by means of 'T' tear that allows horizontal displacement of the sphere according to the x-axis and the forth one, coupled in the third one by means of 'T' connection that allows horizontal displacement of the sphere according to the y-axis by means of step screw of four threads per inch (1.81 mm).

A sphere of 3/16"diameter was fastened in the tip of the screw by means of a screwing-thread, so that it can be traversed along the ultrasonic field. Fig. 1 shows the photo and the schematic of the device for positioning of the sphere.



(a) (b)

Figure 1 - Device for positioning of the sphere (a) photo, (b) schematic

The ultrasonic system is composed of a Panametrics model 500PR pulser and receiver, a Tektronix model TD53012B digital oscilloscope (100 MHz 1.25 GS/s), a Panametrics model A541S piezoelectric transducer (12.7 mm (½") diameter, 5 MHz). In this work, the pulse-echo technique was applied to evaluate the reflection amplitude from the sphere and from internal wall of tube opposed to transducer that will be called the "back wall echo". The reflection amplitude values varied according to the displacement of sphere along z-axis (vertical) and x-axis (horizontal), starting from the reference points (C1, C2 and C3). The reflection ultrasonic signals were registered in spreadsheets files.

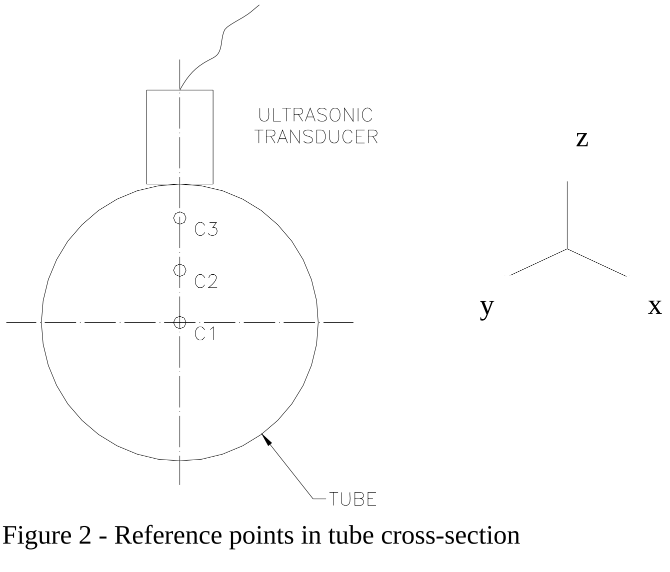


Figure 2 - Reference points in tube cross-section

In this, three points of reference (C1, C2 e C3) were chosen, which are positioned along the y-axis, in the cross-section of tube: the point C1 is located in the center of the tube, the point C2 is located at distance of 17.4 mm from the internal tube close the transducer and C3 is located close the dead zone. Dead zone is a zone close to the transducer where the ultrasonic system is not sensitive to discontinuities. The transducer was located such that its axis coincided with the cross-section axis of tube (y-axis). The tube was full with water and the sphere positioned in a reference point. To focus the ultrasonic beam in the center of sphere, small displacements along x and z-axis was accomplished till maximum attenuation reflection of ultrasonic signal was observed. Fig. 2 shows the three points of reference in cross-section of tube.

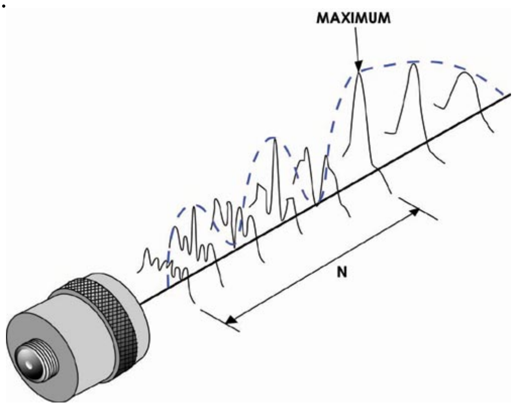


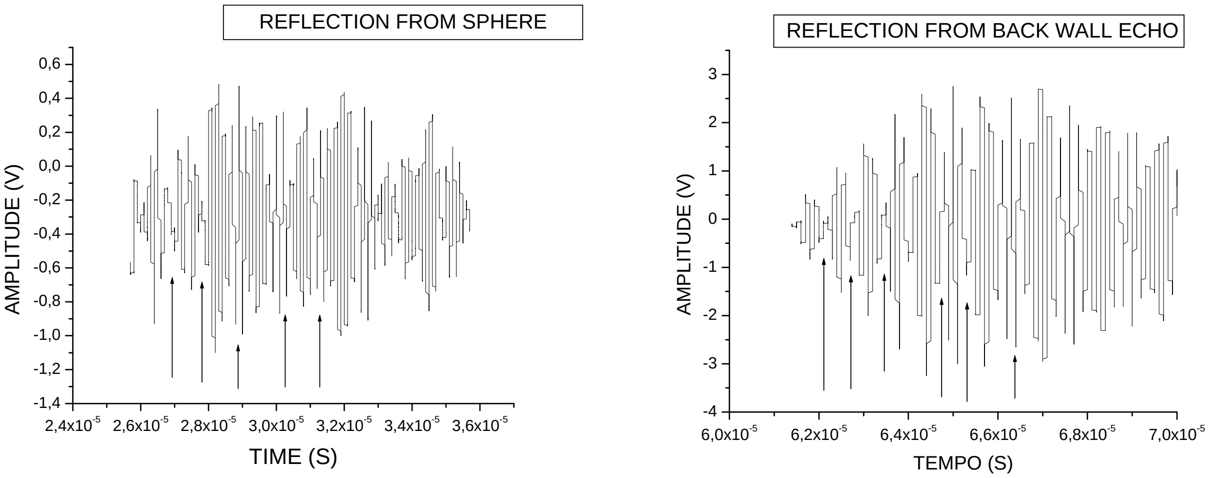
Figure 3 – Pressure sound instabilities along cross-section in front of an ideal piston oscillator. N is near field length

The sphere was located close to transducer and in the region where sound pressure instabilities occur, according to Krautkrämer to Krautkrämer (1990). The discussion about experimental results will be based on these studies. Figure 3 shows a typical drawing ultrasound field where *N* correspond the near-field region. The experimental development was accomplished in Nuclear Engineering Institute (IEN/CNEN), Brazil.

3. RESULTS AND DISCUSSION

3.1 Observed Phenomena

Ultrasonic waves reflected from the sphere and from the back wall are not a single ultrasonic signal, but a group of reflected ultrasonic waves, as the ultrasonic pulse generated by transducer reflects many times in the tube wall thickness and each reflection propagates to water generating one more echo. So, reflected signals from sphere and back wall are constituted of multiple echoes originated from multiple reflections of tube wall thickness. Figure 4 shows reflected wave from sphere and the back wall, with the arrows indicating the beginning and the end of these echoes.

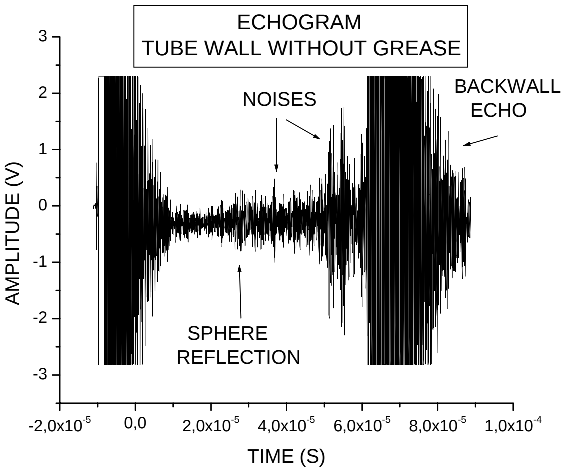


(a) (b)

Fig. 4 - Reflected wave trains from: (a) sphere (b) back wall echo

Another phenomenon observed was the noise occurrence with amplitude values close or larger than one of sphere reflection. Frequency of 5 MHz originate longitudinal and transverse ultrasonic waves reflecting along the circumference of wall tube thickness until coming back to transducer, and also, these longitudinal waves propagate to water and contribute to additional noises. Fig. 5 shows a typical echogram with ultrasonic waves reflected from the sphere and noises. Some noises have amplitudes values larger than the one from sphere.

The hypothesis that the noises were not reflections from the sphere, or other reflective object, but originated by propagation of longitudinal and shear ultrasonic waves was confirmed according to the following procedures: a) the one side of external tube wall, close to the transducer, was coated with liquid Vaseline and after leaning the finger in this covered area the amplitude of main noises was sensibly attenuated, so it was a longitudinal ultrasonic wave propagating in liquid b) Vaseline was removed and all external circumference of tube, close to transducer, was coated with grease. Due to its high viscosity the two main noises were sensibly attenuated, so it was a shear ultrasonic wave propagating across thickness wall tube. Figure 6 shows a typical echogram at the same conditions of Fig. 5, but external tube wall coated with grease. Strong reduction of noises in Fig. 6 can be observed.



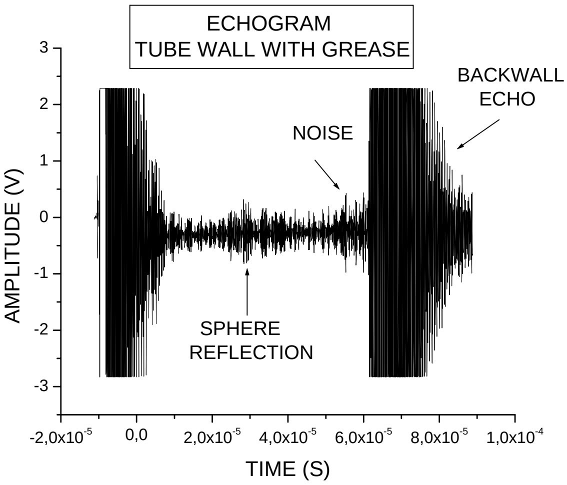
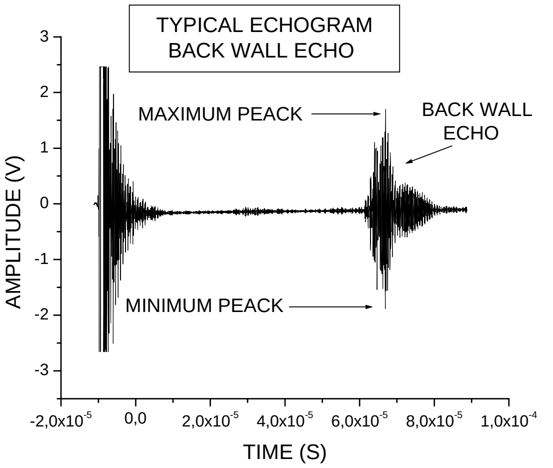


Figure 5 – Typical echogram with noises

Figure 6 – Typical echogram with noises attenuation

3.2 Signal Processing

Figures 7 and 8 show, respectively, typical reflection echograms from the back wall and sphere. These figures correspond to the reflection of the sphere in the same reference point C1, however in different amplitude scales.



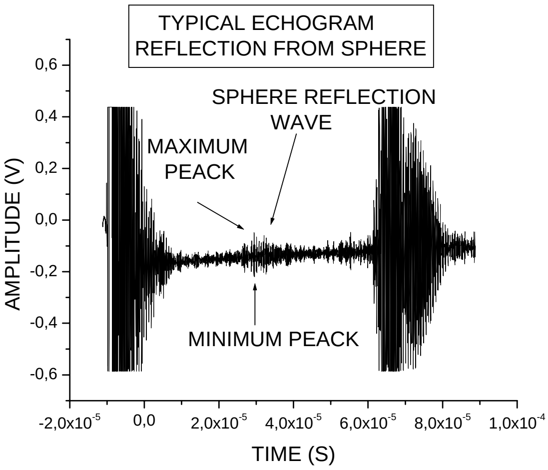


Figure 7 – Echogram of back wall echo (point C1)

Figure 8 – Echogram of reflection sphere (point C1)

These typical echograms were used to calculate peak-to-peak amplitude and the area under the reflected signal curve. The peak-to-peak amplitude corresponds to the difference between the maximum (maximum peak) and minimum amplitudes (minimum peak) of waves train. The areas under the reflected signal curve from sphere or back wall show relationship with the reflected signal intensity.

For the better observation of reflected waves from sphere, smaller value of oscilloscope vertical scale (amplitude) was used and according to increase of the intensity of reflected waves, the scale was modified so that the maximum amplitude (positive or negative) does not cross the up and low screen limits. For this reason there was not a fixed reference to calculate the area under the reflected waves. Then each acquisition was done for the cipher of amplitude medium value signal from reflected waves and an echogram was constructed with absolute amplitude values. Figure 9 shows a typical echogram used to cipher the area under the reflected signal curve.

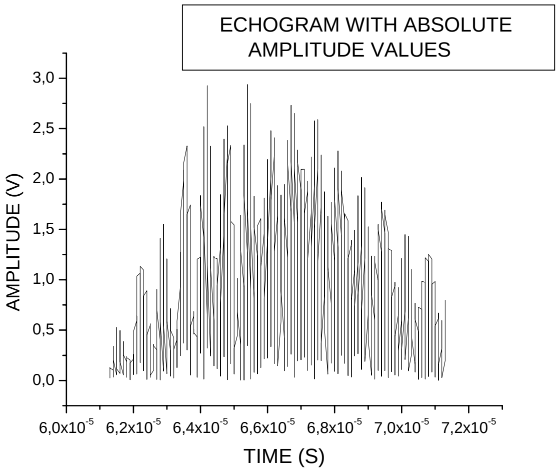


Figure 9 – Echogram with absolute amplitude values of reflected signal from back wall

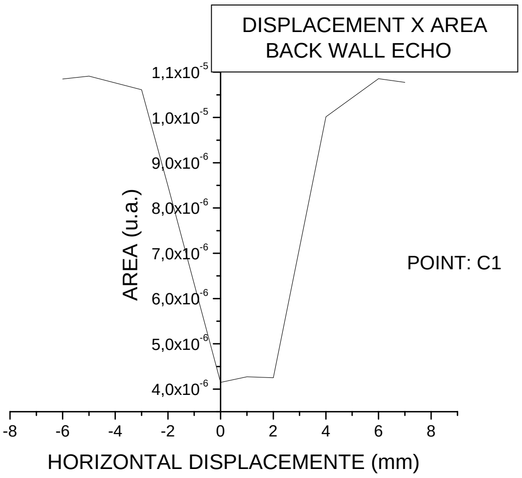
3.3 Horizontal sphere displacement starting from C1 point

3.3.1 Back wall echo

Figures 10 and 11 show the back wall echo variation as function of horizontal sphere displacement starting from the point C1. In Figure 10 the parameter for measurement the back wall echo signal was the area under its curve and in Figure 11 the parameter was the peak-to-peak of the same curve. These figures show similar curves and it is observed that in proportion as the sphere stands back from its maximum intensity reflected signal, to right-hand or left-hand, the area under the curve and the peak-to-peak increase. The sphere interacts with ultrasonic field acting as an ‘amplitude filter’, obstructing the ultrasonic pulse that reaches the opposite wall.

3.3.2 Sphere reflection

Figures 12 and 13 show the ultrasonic reflected wave variation as function of horizontal sphere displacement starting from C1 point. The parameters used in Figures 12 and 13 are respectively the same used in Figures 10 and 11. Figure 12 shows that the maximum area value under ultrasonic reflected waves from sphere happened at 1.0 mm right-hand and it presents a decrease in proportion as the sphere moves. When it moves to left-hand a little oscillation of the area values occur. Figure 13 shows that the maximum peak-to-peak of ultrasonic reflected waves from sphere also happened at 1.0 mm right-hand and it decreases in proportion as the sphere move to right or left. In this point the transducer is sensitive to the horizontal displacement of the sphere.



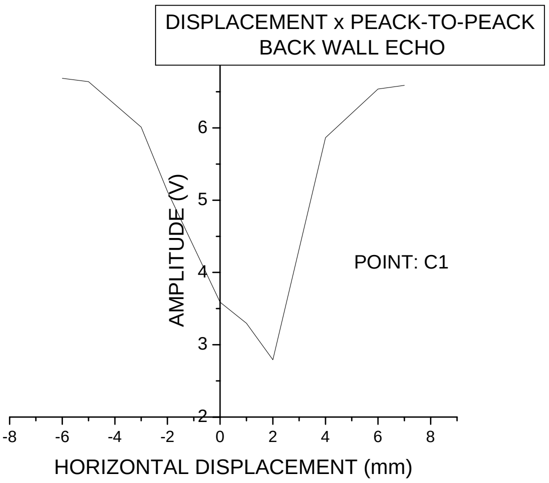
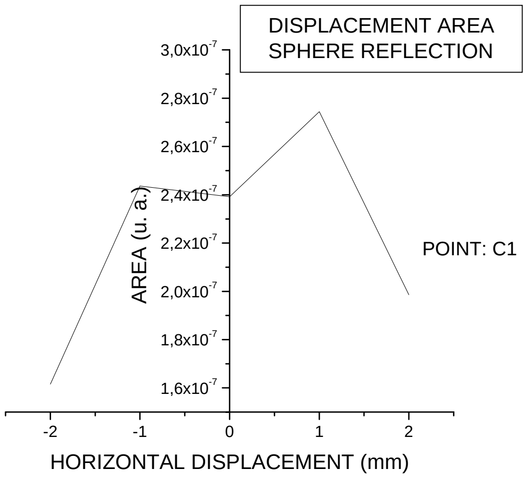


Figure 10 - Area value variation versus horizontal displacement (back wall echo)

Figure 11 – Peak-to-peak variation versus horizontal displacement (back wall echo)



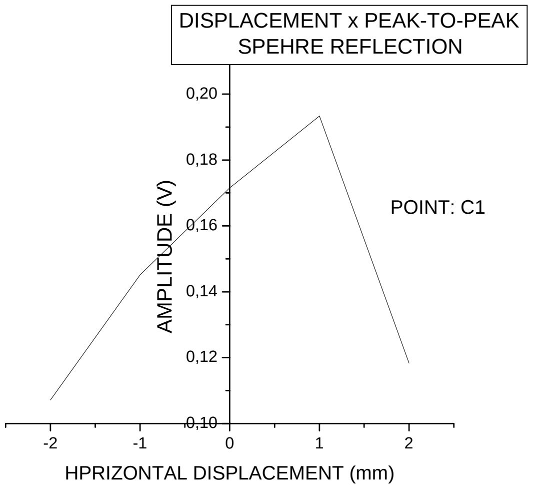


Figure 12 - Area value variation versus horizontal displacement (sphere reflection)

Figure 13 – Peak-to-peak variation versus horizontal displacement (sphere reflection)

3.4 Vertical sphere displacement starting from C1 point

3.4.1 Back wall echo

Figure 14 shows the back wall echo variation amplitude as function of vertical sphere displacement starting from C1 point. The curves for area values and peak-to-peak are very similar, for this reason it will only be shown the peak-to-peak graphics. Compared with horizontal displacement showed in Figure 11, the curve of Figure 14 is similar. The descending displacement of the sphere is presented in the graphs by the negative horizontal axis and the ascending one by positive horizontal axis. The peak-to-peak amplitude back wall echo increases in proportion as the sphere move vertically from C1 point. The descending displacement of the sphere showed smaller peak-to-peak than the ascending displacement, probably because of screwing-thread that fastens the sphere and it attenuates the reflected ultrasonic signal. As in horizontal displacement the sphere acts as an ‘amplitude filter’, impeding that the ultrasonic pulse reaches the opposite wall.

3. 4.2 Sphere reflection

Figure 15 shows the ultrasonic reflected waves variation as function of vertical sphere displacement starting from C1 point. It is observed that the sphere displacement to hand-left exhibits, along almost whole displacement, one continuous reduction of ultrasonic signal reflection probably in reason of screwing-thread that contributed to a continuous attenuation. The sphere displacement to hand-right exhibits swing values, indicating instability of reflected signal, similar to one showed in Fig. 3.

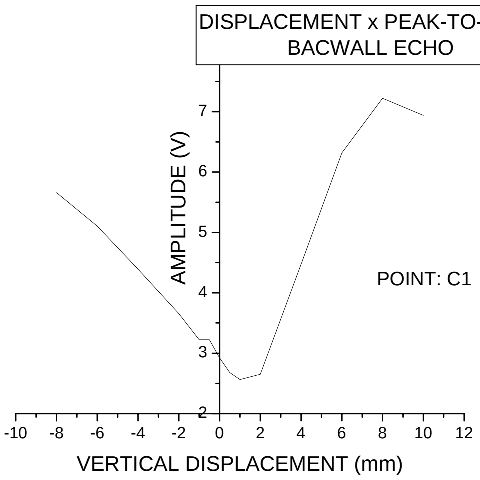


Figure 14 – Peak-to-peak value variation versus vertical displacement (back wall echo)

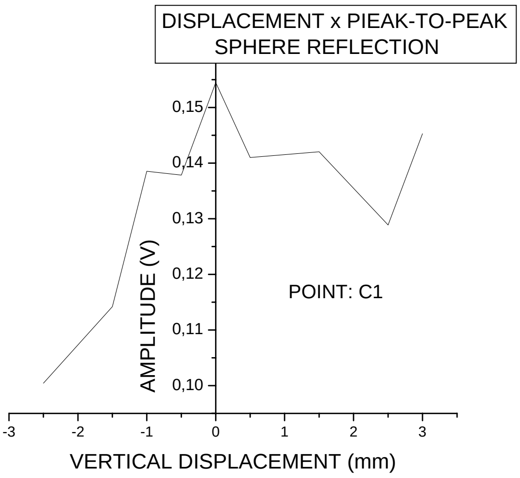


Figure 15 - Peak-to-peak variation versus vertical displacement (sphere reflection)

3.5 Horizontal sphere displacement starting from C2 point

3.5.1 Back wall echo

Figure 16 shows the back wall echo variation as function of horizontal sphere displacement starting from C2 point. A back wall echo instability intensity is observed in horizontal displacement between 7 mm left-hand to 1 mm right-hand. Sphere displacement form 7.5 mm to left-hand and from 2.0 mm to right-hand exhibits a continuous increase of back wall echo intensity until reaching the maximum reflection intensity.

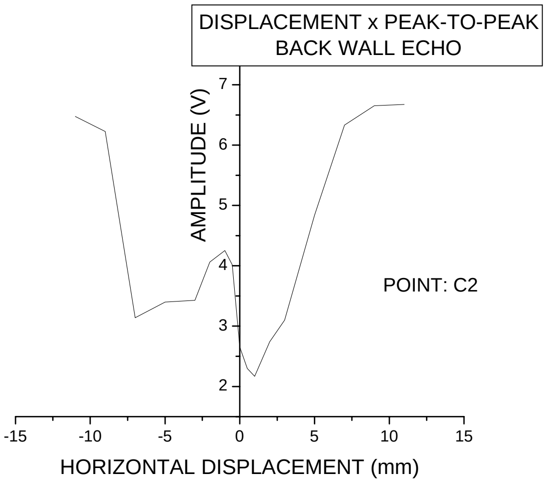


Figure 16 – Peak-to-peak value variation versus horizontal displacement (back wall echo)

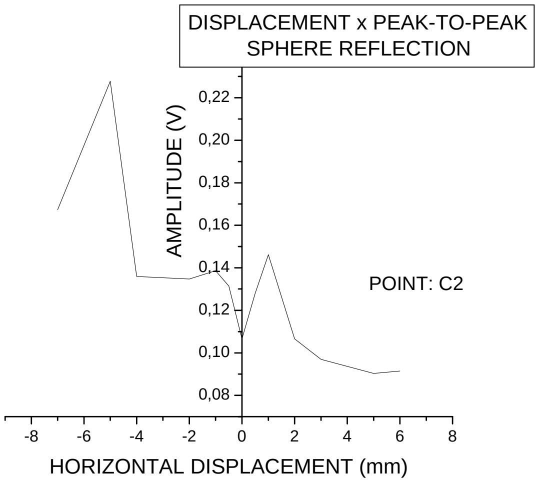


Figure 17 - Peak-to-peak variation versus horizontal displacement (sphere reflection)

3.5.2 Sphere reflection

Figure 17 shows the ultrasonic reflected waves variation as function of horizontal sphere displacement starting from C2 point. A great instability intensity of ultrasonic reflection from sphere is observed, as well as an asymmetry in relation to the displacements of the sphere for right-hand and for left-hand.

3.6 Vertical sphere displacement starting from C2 point

3.6.1 Back wall echo

Figure 18 shows the back wall echo variation as function of vertical sphere displacement starting from C2 point. Peak-to-peak amplitude increases in proportion as the sphere moves up vertically from C2 point, indicating an interaction decline between the sphere and the ultrasonic field, according to observed in C1 point. The descending vertical displacement presents fast peak-to-peak values reduction, probably because of screwing-thread that fastens the sphere and it caused attenuation of reflected signal.

3.6.2 Sphere reflection

Figure 19 shows the ultrasonic reflected waves variation as function of vertical sphere displacement starting from C2 point. A strong reduction of peak-to-peak amplitude is observed immediately after the sphere displacement from its referenced point. Going on sphere displacement, amplitude values oscillations is observed, demonstrating instability in this point. The curve of this one figure shows similar variations as the ultrasonic pressure along the near-field cross-section showed in Fig. 3.

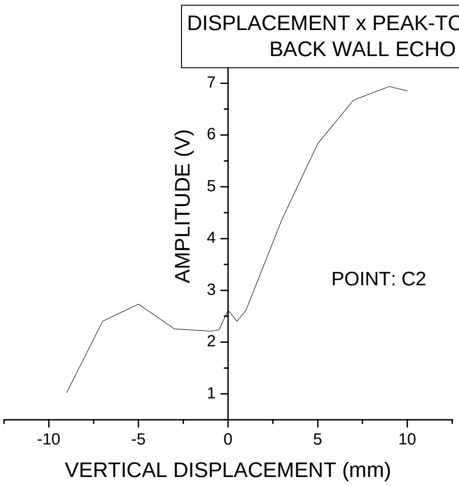


Figure 18 – Peak to peak value variation versus horizontal displacement (back wall echo)

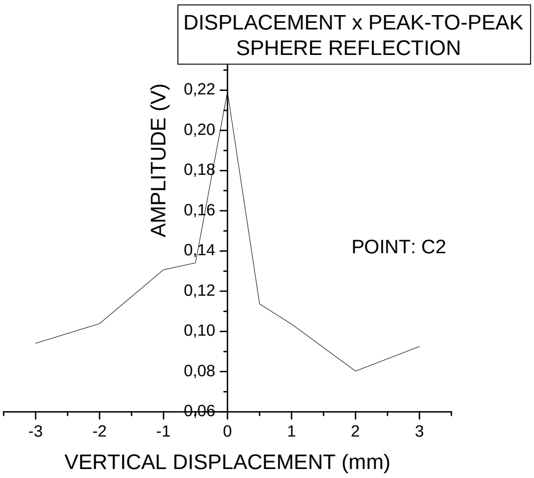


Figure 19 – Peak to peak variation versus horizontal displacement (sphere reflection)

3.7 Sphere perception by transducer

The sphere was displaced from the tube center to internal wall tube where the transducer is located. Initially the sphere was positioned at the tube center that is a distance (Lesf) of 26.4 mm from the internal wall, and after that, the sphere was displaced according to the screw step (1.81 mm) in y-axis direction. To analyze the echograms and differentiate noises from the reflected signal from sphere, the theoretical time propagation was calculated. Table 1 shows the theoretical and experimental times. The theoretical time corresponds to the wave time propagation through stainless steel tube wall, further through the water until it was reflected by sphere and its return to the transducer, which was calculated according to Eq. (1).

$$Tt = 2\left(\frac{Lesf}{Vwater} + \frac{EspTb}{Vsteel}\right) \tag{1}$$

where:
Tt it is the average total time ultrasonic wave propagation,
Lesf it is the distance from sphere center to internal wall tube close the transducer,
Vwater it is the speed wave propagation in water, considered equal to 1480 m/s,
EspTb it is the thickness stainless steel tube, in this experiment same to 2.1 mm and
Vsteel it is the speed propagation wave through steel, in this experiment same to 5900 m/s.

Table 1 – Correlation between the total distance traveled by the ultrasonic signal, emission and return, and theoretical and experimental times propagation.

Total distance Lt (mm)	Time propagation Tt (10^{-5} S)	
	Experimental	Theoretical
28.5	3.96	3.64
19.4	2.60	2.46
15.8	2.14	1.96
14.0	1.86	2.00
12.2	1.31	1.40

Figure 20 shows echograms of reflected signal waves from sphere at different points along the y-axis. Figure 20(a) shows clearly the amplitude reflection from sphere located at the tube center. Figures 20(b) and 20(c) show respectively the echograms when the sphere is located at 17.4 mm and 13.8 mm from internal wall. The perception of amplitude reflection from sphere is not clear and it is only noticed because its time propagation is known. At a distance of 13.8 mm from the internal wall, the amplitude reflection from sphere is smaller than the noise and it gets confused with the same one, being only identified because of knowing theoretical time of propagation of the wave, according to table 1, fig. 20(d) shows this echogram. At distance of 12.0 mm the amplitude reflection from sphere gets confused with the noises and it begins to put upon on the initial ultrasonic pulse, becoming its detection impossible, Fig. 21(e) shows this echogram. The transducer perception used in this work, 5 MHz frequency and ½" diameter, in experiment conditions, does not demonstrate sensitivity for amplitude reflection from spheres of 3/16" diameter immersed in water.

4. CONCLUSION

This paper reports an experimental investigation of the attenuation of the ultrasonic signal by of a steel sphere immersed in water that simulates an air bubble. The ultrasonic pulse-echo technique was applied for the measurement of the attenuation of the ultrasonic waves that were reflected from the sphere and from the opposite wall of the tube. The experimental results show the importance of the transducer diameter and frequency to detect discontinuity immersed in water and the influence of thickness tube. The following conclusions are obtained:
i) the occurrence of multiple echoes is inherent in ultrasonic technique when stainless steel tube is used;
ii) the transducer does not demonstrate sensitivity for amplitude reflection from sphere close to it;
iii) low frequency transducers propitiate formation of noises that disturb the signal interpretation, therefore frequency and diameter transducer influence in technique application.

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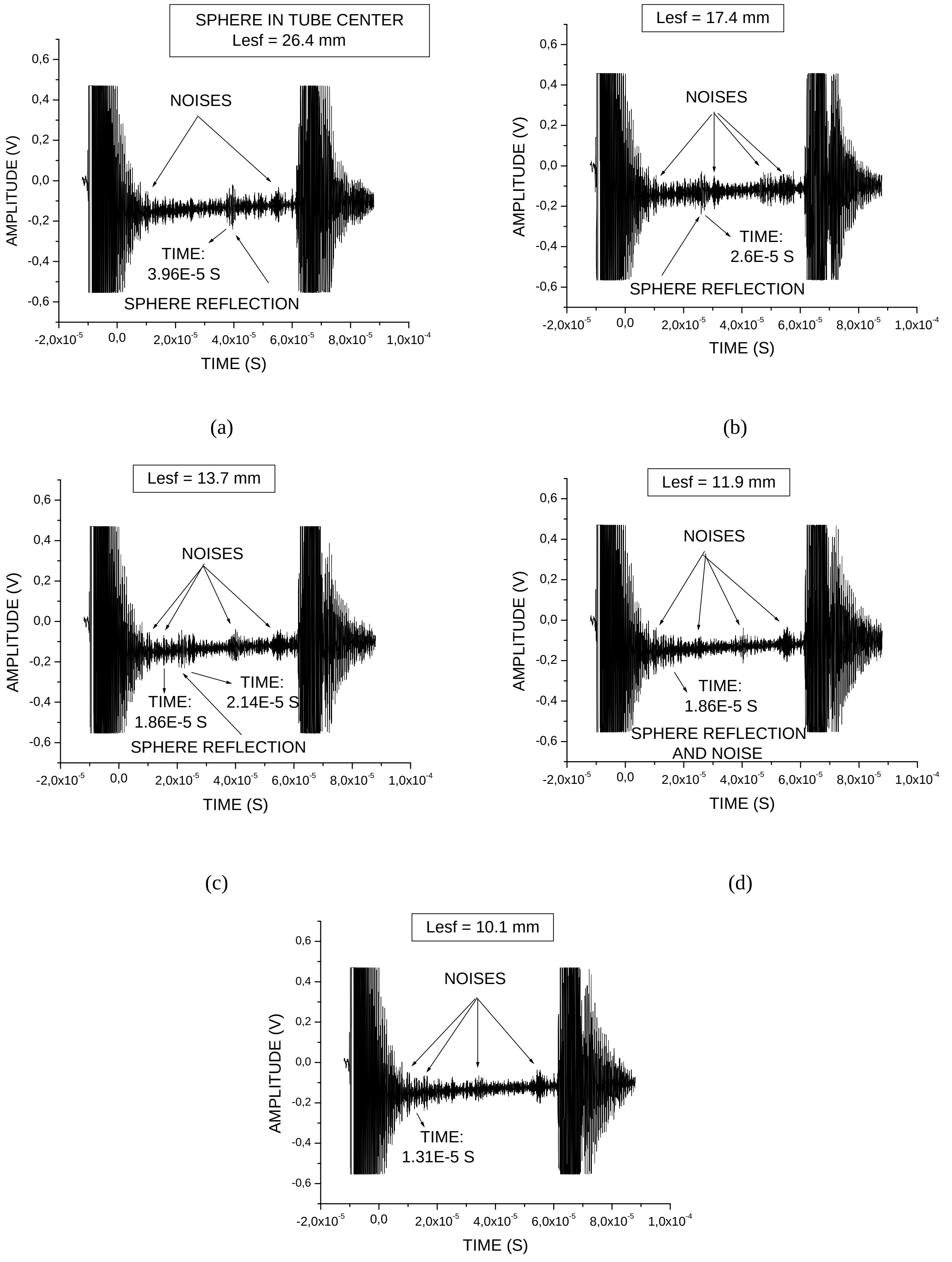

(a) (b)

(c) (d)

(e)

Figure 20 – Echograms of reflected signal waves from sphere in different points along the y-axis: (a) 26.4 mm, (b) 17.4 mm, (c) 13.7 mm, (d) 11.9 mm e (e) 10.1 mm.